LNG LOGISTICS UNDER ARCTIC CONDITIONS

Master Thesis – Final Review | Catalina Higuera
MSc. Thesis

LNG Logistics under Arctic Conditions

Maria Catalina Higuera Rueda
MSc. Transport, Infrastructure and Logistics
Delft University of Technology
Shell Global Solutions International

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Graduation Committee:
Chairman : Prof. dr. ir. Lori Tavasszy (TU Delft, TBM)
Supervisors : Dr. Marisa de Brito (TU Delft, TBM)
Dr. ir. Jaap Ottjes (TU Delft, 3mE)
Ir. Gonneke Bakker (Shell)
Dr. Wouter Meiring (Shell)
Preface

This report is the results of the research project executed at Shell Global Solutions in The Netherlands. It is the master thesis for the Technical University of Delft’s Master Program in Transport, Infrastructure and Logistics (TIL). The research project took place during an internship at the LNG Design Team in the LNG (Liquefied Natural Gas) Department for Process and Technology located in Rijswijk.

For my graduation thesis I really looked for the opportunity to do it on a practical subject that would be of interest for a company. I was very happy when I found the opportunity to develop this research project at Shell since it grouped the elements I was hoping for. The challenge to have logistics in a new environment as Arctic was very interesting and motivating. Also having shipping as a transport mode to be evaluated and the supply chain for Liquefied Natural Gas (LNG) were all exciting subjects I had never had contact before.

During this internship the familiarization with the Arctic area, its characteristics and weather condition was first done. Further the analysis of the Arctic weather impact over the LNG supply chain and the evaluation for a robust concept was done. This report shows the results of the research made and provides the first step to continue in the development of study in the Arctic LNG supply chain business.

Being able to do this project in Shell and get to know experts in the different areas related to my thesis made the whole experience complete. Without the support of the people from the teams I worked with, the success of this project wouldn’t have been the same. That’s why I would like to thank first my Mentor Wouter Meiring and Supervisor Gonneke Bakker for their support and inspiring ideas. Thana Mousawi for introducing me into Shell and being able to join the LNG Design Team, also the evaluation committee at the TU Delft for their constructive comments, and finally all other teams I worked with during my internship.

Finally, I would like to thank my family for their support throughout my study.

Catalina Higuera
Rotterdam, June 2011
### Abbreviation list

<table>
<thead>
<tr>
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<th>Definition</th>
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<tbody>
<tr>
<td>cm</td>
<td>Centimeters</td>
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<tr>
<td>cm/sec</td>
<td>Centimeters per second</td>
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<tr>
<td>IMO</td>
<td>International Maritime Organization</td>
</tr>
<tr>
<td>IRR</td>
<td>Internal return rate</td>
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<tr>
<td>km²</td>
<td>Squared kilometers</td>
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<tr>
<td>KPI</td>
<td>Key performance indicators</td>
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<tr>
<td>LNG</td>
<td>Liquefied natural gas</td>
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<tr>
<td>LNGC</td>
<td>Liquefied natural gas carriers</td>
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<tr>
<td>m</td>
<td>Meters</td>
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<tr>
<td>m/s</td>
<td>Meters per second</td>
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<tr>
<td>Mtoe</td>
<td>Million tons</td>
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<tr>
<td>mtpa</td>
<td>Million tons per annum</td>
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<tr>
<td>nm</td>
<td>Nautical miles</td>
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<tr>
<td>NPV</td>
<td>Net present value</td>
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<tr>
<td>RMRS</td>
<td>Russian Maritime Register of Shipping</td>
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<tr>
<td>SALSA</td>
<td>Shell’s Advanced LNG Supply Chain Application</td>
</tr>
<tr>
<td>VLCC</td>
<td>Very large crude carriers</td>
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<tr>
<td>WWF</td>
<td>World Wildlife Fund</td>
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Summary

As energy demand increases, easy to reach hydrocarbon resources are reducing. Arctic is the new exploration frontier and it is expected to hold about 30% of the world’s remaining undiscovered oil and gas reserves. Natural gas has become a preferred fuel, due to its low carbon emissions. To transport natural gas from the Arctic to its markets, liquefaction is the preferred state. The remoteness and distance from Artic are the main reason for this preference. The liquefied natural gas is then transported in shipping vessels which are affected by the extreme weather conditions found in Arctic; during the winter and spring: sea ice, icebergs, low temperatures, and complete darkness, and for the summer and fall: fog, waves and mammal migrations. The available window to perform logistics without hindrances is significantly reduced in this area.

Experience on how to deal with Arctic and the effect the weather has over the LNG supply chain needs to be assessed. Therefore the objective of this study is to identify a robust supply chain concept for LNG under Arctic conditions by comparing supply chain concepts against pre-defined performance indicators. By means of using a simulation tool, the analysis of the LNG supply chain can be done. However a methodology to implement Arctic conditions will be developed during the course of this project as it hadn’t been done before with this simulation tool.

In order to complete the project, first understanding the Arctic, its conditions and the process for LNG and its supply chain were necessary. A series of supply chain concepts for Arctic operation was developed. Later through experts consultation a selection of concepts was made and later used for the implementation of a simulation: Arctic conventional, Ship to Ship transfer and Hub to Ship transfer.

An example case located in the Arctic is used as the case study to develop the LNG supply chain simulations and analysis. The data collection started with the sea ice information over the route to deliver the LNG to a specific market location. This ice information had three different scenarios: Heavy, Average and Mild ice along the route and also a 30 years historic ice data was obtained. On the supply chain design, some of the variables in the LNG Supply Chain are storage capacity, ship’s cargo capacity, ice carrier fleet size, also for this case, the hub storage size and the open water fleet size. Creating the supply chain characteristics was first done using a calculation tool to determine fleet sizes, using the ice information available for the route. After this the simulations were run, by defining different characteristics for each of the three supply chain concepts to be evaluated.

The results obtained from the simulation were compared in terms of production reached (percentage over maximum production designed, number of lifts), number of tank tops and their duration, utilization of storage tank, ships and berths. Also economics on Capex.
and Opex were considered, so the balance between investment and revenues could be assessed. The final decision on which supply chain was delivering best results was a combination between operation and financial performance over different ice scenarios and a final test over a 30 years historic data with variable ice.

The research project allowed to conclude that for the study case the use of different ice scenarios (heavy, average or mild) in the design phase are determining certain levels of risks for not delivering what the production level is designed for. For example in this case an average ice severity scenario has been found to be a good assessment base of the supply chain design performance. In the average ice scenario, against a historic data, the designed supply chain is able to deliver most of the designed production with acceptable financial indicators (no over spend for redundant capacity was required). Based on these ice scenarios, the simulation are behaving as it was expected and this support further what was believed for Arctic supply chains. The design of a supply chain influenced by Arctic conditions will be robust due to the capacity implemented in the design. Redundancy of some of the supply chain elements is one of the strategies to achieve the objective of this research.

The simulation tool used for this project allowed to have detailed results, but simple calculations can help understand the problem and further create scenarios. Icebreakers assistance is an important operation to include for Arctic logistics and is an interesting research item to work on future projects. For future project, historic data is not recommended; instead the use of expected ice due to climate change could be an important factor to be considered in Arctic projects.
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1. Introduction

This chapter gives an introduction on this thesis subject. Sections 1.1 and 1.2 present the challenges that energy companies face to satisfy the demand on fossil fuels. From this point, a set of objectives and research questions are formulated to give the base of the research project in sections 1.3 and 1.4 with the corresponding scope defined for the project as described in section 1.5. Finally sections 1.6 and 1.7 will present the approach used and the methodology designed to obtain the results for this project.

1.1. Background

By the middle of the 21st century the world's energy usage is expected to have been doubled. Energy companies are exploring ways to respond to this demand and are willing to go the extra mile to find the resources required to fulfill it. Among the unexplored areas the Arctic is becoming more attractive. Climate change and retreating ice in the summer season have made the Arctic accessible for longer periods of time. Therefore, existing technologies can be easily adapted for extraction of hydrocarbons in this area. Nevertheless, energy companies should be aware that the Arctic remains a harsh environment to work in. Consequently more planning and research is being carried out to enable safe and secure Arctic operations.

Shell is one of the companies that have continued to invest in Arctic research in different technology development areas. It is believed that the Arctic is rich in hydrocarbon resources, mostly natural gas. Hence, the development of infrastructure to extract these resources is gaining interest. Due to the remoteness of the Arctic, the preferred way to transport Natural Gas is as Liquefied Natural Gas (LNG) by means of sea shipping. This approach has several challenges of its own, specially operating under the Arctic conditions.

Even though climate change has improved the accessibility of the Arctic during the summer period, the extreme cold during the winter season and the presence of sea ice gives limitations. The Arctic environment and weather variations between seasons have proven to be an interesting case to be studied for the Supply Chain of LNG. The necessary use of icebreakers, sea ice, complete darkness during the winter, high waves and low visibility during the ice free season are just examples of conditions that affect the logistic process. Each condition will have a different impact on the LNG supply chain.

The necessity to design a LNG supply chain that is able to deal with most of the affecting factors was the main driver of this particular study. The objective to identify a robust supply chain concept for LNG under Arctic conditions by comparing supply chain concepts against pre-defined performance indicators is defined. In this case, the term composed describes the gathering of elements available in the LNG supply chain to create concepts that will be evaluated. This goal has set the base to start the following research, to identify Arctic's characteristics and weather conditions affecting logistics, the production of LNG, actors involved and concerned about the Arctic and the analysis of the supply chain concepts.

1.2. Problem definition

World energy demand in fuels and renewable energy has been increasing and expected to continue with this trend at least until 2030 as the report for World Energy Outlook 2008

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states (International Energy Agency, 2008, p. 78). In Figure 1.1 the rising trend of energy consumption by means of the different sources of energy available can be observed. The interest to use renewable energies for low carbon emissions is growing but the switch from non-renewable energy sources cannot take place suddenly in order to maintain economic prosperity. Therefore fossil fuels will still play a role to bridge the gap to a low carbon energy future. As natural gas is considered to be a cleaner burning fuel the demand of natural gas will increase at 1.8% each year between 2006 to 2030 and its share in world primary energy will move up slightly, to 22% in 2030 (International Energy Agency, 2008). This demand is increasing by the operation of new power plants, using high-efficient gas turbine technology and the environmental advantage as a clean burning fuel (Shively & Ferrare, 2005). Unfortunately the distance between customers and natural gas sources is not always convenient and currently the local sources are not sufficient to meet medium to longer term demand. Therefore transportation of the natural gas usually presents challenges.

![Figure 1.1: World primary energy demand fuel (International Energy Agency, 2008)](image)

Easy to access oil and gas may be declining; consequently Energy Companies are exploring new frontiers to find resources. For decades the Arctic has been of interest since oil production began in the late 1960’s. Today, Alaska, Canada, Norway and Russia are the main Arctic production areas, but most of the Arctic, especially offshore, remains unexplored. Due to the world’s energy demand doubling, Arctic’s expected vast oil and gas resources could help meet some of that rising energy demand, if developed responsibly.

The experience in Arctic conditions is still low and further research to make projects economically viable is key for the future production of oil and gas in this area. With climate changing and ice retreatment over longer periods of time, the possibilities to reach remote locations in the Arctic by sea are increased by opening up as shipping routes which weren’t available before. The opportunity to reach unexplored areas has raised the interest of companies to find out ways to work under Arctic conditions.

Typical Arctic conditions are characterized by: low temperatures, darkness during the winter, icing, sea ice, waves and fog during the summer. Moreover the remoteness of the fields in Arctic adds a further gap to reach the demand markets and due to the environmental condition installation of facilities for production and transport is more difficult. Both issues of Arctic environment and distance limit the alternatives to transport natural gas into the market. As shown in Figure 1.2 due to distance the economic costs increase, therefore for transporting natural gas, Liquefied Natural Gas (LNG) offers an interesting alternative to reach distant markets.

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Liquefied Natural Gas (LNG) is transported in specialized designed shipping vessels. However, sailing through Arctic waters faces extreme ice, cold, and other weather conditions that impact the shipping capacity. Though the supply chain simulation currently used by Shell does not include the ice and weather conditions as found in the Arctic, this is the reason to start a research project for LNG Logistics in Arctic conditions.

Since Shell currently is analyzing prospect projects in the Arctic, there is a need to develop a supply chain concept that includes the set-up, conditions, and limitations of the Arctic as part of the feasibility investigations. The Supply Chain Concept has to comply to pre-defined performance indicators that Shell has established to be important based on past projects experience.

1.3. **Main Objective**

According to the problem description, described in the previous section, leads to the following main research objective:

**To identify a robust supply chain concept for LNG under Arctic conditions by comparing supply chain concepts against pre-defined performance indicators.**

The term composed indicates the gathering of elements available in the LNG supply chain to create concepts that will be evaluated upon pre-defined performance indicators. These performance indicators are given by the Company and will be the base to compare and identify which concept is more robust for the LNG Supply Chain under Arctic conditions.

To be able to accomplish this objective, a research methodology and research questions will be described in the following chapters for the development of the thesis project.
1.4. Research Questions

First, based on the main objective intended to be reached by the development of this research project, a main question to be answered can be stated as follows:

How can existing elements of the LNG Supply Chain be integrated in order to obtain a robust concept for an Arctic environment?

Related to the main objective, this question will deliver the knowledge needed to achieve the goal of identifying the robust concept for LNG Supply Chain under Arctic conditions. This question implicates that different elements for the LNG Supply Chain will be assembled to deliver concepts that will be simulated and evaluated based on pre-defined performance indicators.

A secondary set of research questions has been identified in order to structure the project. The answers from these questions should lead to give insights and reach the main objective described before.

<table>
<thead>
<tr>
<th>Question</th>
<th>Answered sections</th>
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<tr>
<td>What are the elements and the stakeholders involved in the supply chain for LNG?</td>
<td>Ch. 3 and 4</td>
</tr>
<tr>
<td>What methods to develop a supply chain can be applied to achieve different LNG supply chain concepts for Arctic conditions?</td>
<td>Composition made in Ch. 4</td>
</tr>
<tr>
<td>Is it possible to group areas with similar characteristics in the Arctic? How do these conditions (weather, darkness, ice) limit operation for production of LNG?</td>
<td>Ch. 3</td>
</tr>
<tr>
<td>Which are the key supply chain elements for the logistics of natural gas export in Arctic conditions?</td>
<td>Ch. 4</td>
</tr>
<tr>
<td>What evaluation method is appropriate and which indicators are suitable to determine the performance level of a supply chain?</td>
<td>Ch. 5</td>
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1.5. Boundaries

Bearing in mind the time constraint, there are some boundaries set to the scope of this research project:

- Not all of the supply chain concepts will be investigated in-depth using the available simulation tool.
- It is assumed that the LNG is produced on one production location in the Arctic and although it will in real life be delivered to various consumer locations, there is only one delivery location selected for this research project. This is justified as the focus of the study is on the Arctic conditions and the delivery locations are all in open water conditions.
- The Natural Gas production and liquefaction plant is not evaluated or analyzed as part of this project. The plant design and infrastructure will be a basic design assumed from a standard Natural Gas production facility, with a seasonal LNG logistics under Arctic conditions
production. The seasonality of the LNG production is fixed for all simulations and is not related to outside temperature.

- Characteristics of the ships will be according to what is available today, no shipping design or defining new requirements will be considered during the development of the project.
- The stakeholders will be described, but a stakeholder approach will not be developed nor any alternatives in possible partnerships.
- The consideration of future conditions in the Arctic (e.g. Climate change, ice melting, etc.) will only be mentioned but not taken into account in the evaluation of the concepts or in the detailed evaluation of the selected concept as no reliable information is available.
- Specific geographic locations will not be considered for the LNG production location. For the detailed investigation of the selected concept a location is used for which sufficient data is available.
- Programming and code writing for the simulation tool will not be done. The available simulation tool will be used as far as possible for obtaining results and programming will be done by a third party hired by the company if approved.

1.6. Research approach

The methodology used to obtain results to find a robust LNG supply chain under Arctic conditions developed along with the project. Discussions with experts in natural gas and LNG processing, LNG supply chain, Arctic and project development, took place constantly to verify the right approach was being used. The steps used during this project are:

![Methodology diagram]

The definition and understanding of the problem took some time in order to define exactly what kind of data was required. The data had to be not only for related processes of LNG but also the supply chain and how it can be affected by factors of weather, production, market, location, etc. Learning about the supply chain of LNG and the utilization of Shell’s simulation tool was the first step into mapping the conventional supply chain of LNG.
Once the processing of LNG to the market was clear, the definition of the Key Performance Indicators was easier to understand. The key performance indicators were taken from experience of people dealing with Supply Chain problems, logistic issues with projects of the company and Arctic knowledge. Since the definition of what it was that the supply chains should be doing from the key performance indicators perspective, the Arctic conditions was then analyzed to verify how these could impact over the key performance indicators and made also possible the refining and research of more detailed collection of information.

Having the basic concepts of LNG Supply Chain and the knowledge of Arctic, the combination to create concepts that could deliver LNG with an Arctic perspective was completed. This same combination of knowledge allowed having good criteria to select the most feasible supply chain concepts. Jumping into the simulation took more analysis as the options would have been immense without a first look on how to build up the supply chain scenarios. Not only on the selection of the elements of the supply chain, but also the selection of what kind of information would be implemented to simulate Arctic conditions. The pre-selection was then extended, not only to decide on a supply chain concept, but also on the use of Arctic data and supply chain elements characteristics.

Finally after the decisions were taken, the simulations run were done. A detailed analysis considering the key performance indicators was done, to be able to identify the best performing supply chains in the ice conditions that were implemented in the simulation. At the same time, a financial evaluation took place in order to balance the returns over the supply chains against the investment and operation costs for each one of them. The Supply Chain concept assessment was then finished with verification over a variable ice scenario from historic data which could test the capability of the supply chain to deal with disruption in its flow, in this case created by sea ice.

The process is found to be detailed and critical over the decision taken. It considers information and process which expert within the company consider complete and important for future evaluation of projects to be developed in Arctic.

1.7. Research Approach

The research and consequently the report, is set out to accomplish the main objective and answer the research questions. Therefore all of the research parts (and report) are correlated with them. Thus, the way to explain the logic behind the report set up is correlating with the main objective and research questions.

The result of the methodology used to complete the research project is summarized in Figure 1.4. From the steps taken, different chapters have been created to compile the answers found for the completion of the master thesis. Each of the blocks found in the figure represent each of the chapters found in this report and some of the contents within each chapter.

The first chapter describes the background information to support the realization of the project. Within this chapter the main objective and research questions to be achieved can be found. From this point the direction of the project is established and therefore the second chapter contains the literature overview which can serve as the drive on a theoretical point for some of the concepts used in further chapters. In Chapter 2 definitions for supply chain, performance indicators, robustness and financial evaluation can be found. The next step is to continue with the location where the project is focusing on. This location is defined as Arctic since it has become an interesting area to explore for new oil and gas reserves. First the main difficulty to perform logistics in Arctic is the environmental conditions and their seasonality. This will results in diverse risks to be
considered for a logistics operation. Second stakeholders in Arctic play an important role. Approaching some of these parties will prove crucial for a company that is planning to develop projects in the Arctic area. Finally climate change is mentioned and how increase in exploration in Arctic will become a reality.

In Chapter 4 the description of the LNG supply chain and the alternatives for an Arctic location are described in the first sections of the chapter. A selection of some supply chain concepts is done with the help of experts to determine each concepts' feasibility. Then the details of the simulation tool to be used, its input and the outcomes looked for after the simulations will be critical for the evaluation of the different cases to be simulated. Chapter 5 contains all the subjects related to the example case used to analyze a prospect project in an Arctic area. It will begin with the assumptions used to set-up the example case. According to the project’s potential location, its Arctic characteristics should be considered for an analysis of the route conditions to calculate the requirements for supply chain concepts from the selection made in the previous chapter but now implemented to the example case. These results will set the context to perform the simulations in the tool used by Shell. The outcome obtained from the simulations is compared against different scenarios of ice, from which results a first robustness assessment is made. As different supply chain alternatives deliver similar operational performance behavior a financial evaluation gives the balance to find the equilibrium between operational and financial performance. Finally the main robust evaluation is done by means of a long term simulation under variable ice conditions to determine how each supply chain alternative from the previous selection can withstand the disruptions of ice from 30 years historic data.

To finalize this report Chapter 6 groups from the lessons learned what could be done to improve the results for other similar research projects. At last Chapter 7 aims at describing the conclusions for this research project, directing to give an answer to the main objective of the research project and also short points of recommendations to keep in mind for future projects.
4. LNG Supply Chain Evaluation over an example case

- Energy demand
- Natural gas as clean source of energy
- Arctic new exploration destination
- Transport and delivery of natural gas

2. Literature Overview

- Supply chain concepts and distribution strategies
- Supply chain performance
- Robustness concept
- Financial evaluation

3. Arctic Logistics

- Geographical location
- Weather conditions
- Arctic seas characteristics
- Arctic shipping and its operations
- Arctic stakeholders

4. LNG Supply Chain

- Arctic LNG supply chain concepts and selections
- LNG supply chain vulnerability to Arctic conditions
- Simulation tool and key performance indicators

5. Evaluation over an example case

- General assumptions
- Ice conditions on shipping route and impact over voyage duration
- Preliminary calculations for fleet size requirements
- Simulation results and analysis
- Robustness evaluation
- Financial evaluation

6. Future Implications

- Climate change influences
- Icebreaker support
- Further simulations
- Assessment tool

7. Conclusions and recommendations

- Supply chain concepts and evaluation method
- Implication to development in input information (e.g. climate change, case data, etc)
- More simulation cases to obtain results for assessment tool
- Ice impact and ice management (icebreakers) for simulation implementation

Figure 1.4: Report structure
2. Literature overview

Key concepts to be used along the research project will be described in this chapter. Currently some research is being done in optimization of logistics for different products related to oil production. These are more focused in optimization than evaluating the robustness of the supply chain. Some examples are: Nikolaou (2010), and Grønhaug & Christiansen (2009). For the case of Arctic, no articles were found related to assess the impact of ice in the supply chain. Instead articles more related to the opportunities, difficulties and operation profiles under Arctic conditions could be accessed. How to deal with sea ice in shipping and the opportunities that transporting through the Arctic compared to other shipping routes can be obtained in Internet and different journals. Literature that could assist in the completion of this specific research project up to now was not obtained; therefore general concepts to design and evaluate the supply chain of LNG under Arctic conditions are described.

2.1. Supply Chain concepts

2.1.1. Supply chain distribution strategies

Typically, there are three main distinct outbound distribution strategies used for supply chain design. Either one of them or a combination can be implemented in the supply chain of a product; but at the end the suitable supply chain design for a particular situation, product, or company can only be selected by carefully considering the specific characteristics of the situation. The strategies as described in the book “Designing and Managing the Supply Chain” (Simchi-Levi, Kaminsky, & Simchi-Levi, 2000) are:

1. Direct shipping:
   - Items are shipped directly from supplier to customer without going through distribution centers.

2. Warehousing:
   - This is the classical strategy in which warehouses keep stock and provide customers with items as required.

3. Cross-docking or Transshipment:
   - Items are distributed continuously from suppliers through warehouses to customers. However, the warehouse rarely keeps the items for more than 10 to 15 hours or in the case of transshipment almost immediate.

These strategies are easily adapted to the supply chain of LNG and will be used in a later chapter.

2.1.2. Performance indicators for Supply Chains

Most organizations use measures of performance to analyze and evaluate their efficiency and progress over time. Performance indicators are a critical point of view for managing a business and determine if desired results are being obtained. The importance of applying performance indicators to measure a business performance is better described by Fawcett and Cooper’s article, where they state that “performance measurement is critical to the
success of almost any organization because it creates understanding, molds behavior, and leads to competitive results” (Fawcett & Cooper, 1998). Supply chain operations have different ways to be evaluated and eventually these results could be linked to financial performance of a project or the organization. According to Coyle et al. (2009) the characteristics of good measures should be that: “is quantitative, is easy to understand, encourages appropriate behavior, is visible, is defined and mutually understood, encompasses both outputs and inputs, measures only what is important, is multidimensional, uses economies of effort, and facilitates trust.” The key point to keep in mind is to set measurements that are able to portray the essence of the supply chain process, focusing on what is important to the supplier and customer.

Some examples of measurements used to evaluate the supply chain performance can be seen in Table 2.1:

<table>
<thead>
<tr>
<th>Performance attribute</th>
<th>Measurements</th>
<th>Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply chain reliability</td>
<td>On time delivery or lead time</td>
<td>Percentage – Days</td>
</tr>
<tr>
<td></td>
<td>Order fulfillment</td>
<td>Percentage</td>
</tr>
<tr>
<td>Flexibility and responsiveness</td>
<td>Response time</td>
<td>Days</td>
</tr>
<tr>
<td>Costs</td>
<td>Total delivery cost</td>
<td>$ or $/unit</td>
</tr>
<tr>
<td>Assets utilization</td>
<td>Net asset turns</td>
<td>Turns</td>
</tr>
</tbody>
</table>

These are a couple of examples found in the literature, however “every company needs to understand its own unique environment and determine its measurements based on that insight.” This translates into every company and supply chain should be able to define their own ways to measure performance and the LNG supply chain is not different. The detailed performance measure will be described in a later chapter, to know what is important for the LNG supply chain and its simulations.

2.2. Robustness concept

Reliable delivery of the product to the customers is the essence of a supply chain. Different events are constantly threatening this core function of the supply chain, increasing the risk of interruptions. Consequently companies aim at being prepared, plan and have alternatives for their supply chain to overcome disruptions and guarantee the delivery of products with a robust supply chain.

Understanding the concept of robustness is one of the important steps for the assessment that will be made on the supply chain designs simulated for this study. The performance indicators will indicate how the concept of robustness is being considered in theory and how can it be improved for Arctic operations.

Vulnerability to a disruptive event can be viewed as a combination of the likelihood of a disruption and its potential severity. Any company could assess the supply chain vulnerability by answering the following proposed questions by Sheffi (2005):
- What can go wrong?
- What is the likelihood of that happening?
- What are the consequences if it does happen?
- What should be the focus (priorities)?
- What can be done to reduce the probability of disruption? (Attack problem source)
- What can be done to reduce the impact of a disruption?

A good way of seeing the confluences of probability and consequences of events is by a matrix with these two dimensions of vulnerability. As seen in Figure 2.1 the vertical axis is the probability of the disruptive event and the horizontal axis represent the magnitude of the consequences. This relates to the understanding of what could go wrong in a business and the impact over results. Depending on the quadrant the combination between probability and consequence reaches an alternative reaction can occur. In the figure a list of different levels of alternatives to overcome the disruption and reduce its consequences is shown to the right side of the figure.

![Figure 2.1: Dimensions of Vulnerability (Sheffi, 2005)](image)

Redundant capacity is one of the options after identifying a Company's vulnerability points. Even though this is not a cheap alternative, the failure to maintain a redundant process might risk the entire company and therefore it is important to make a decision on how to protect it or alleviate potential disruptions.

Other alternatives are: extra inventory, spare capacity, added workers and low utilization can help a company recover from a disruption, but lean manufacturing and supply chain operation as just in time to reduce cost in safety stock, outsourcing to create more flexibility have influenced productivity. Having a lean structure doesn’t mean imminent trouble, but at least the company should be aware of any problem situation and have a plan in case it needs to respond. Being flexible is the best way to achieve supply chain resilience. This flexibility is created by many means like training of employees, close relations to suppliers, customers and mainly have a plan to respond or begging with avoiding disruptions.
2.3. Financial evaluation

Investing on elements for a supply chain involves costs and benefits spread over a period of time. Companies need a decision making base to evaluate whether to invest or not, justified on expected future benefits. Therefore comparing values of money cash flows at different dates requires the use of financial indicators that reflect the value of money through time. To do this, during this research project a financial evaluation will be made to compare the cash flow of the benefits obtained from different supply chain concepts (LNG produced) against the approximation of required investment and operation costs.

The initial value is of course the investment to have the supply chain elements considered for each supply chain design. From there the values considered for the cash flows over time are as stated by Brealey, et al (2001) in the following formula:

\[
\text{Cash Flow}_t = \text{Sale Revenues} - (\text{Operation Costs} + \text{Cost of LNG} + \text{Cost of LNG Lost Sales})
\]

From this formula to calculate the cash flows a Net Present Value (NPV) and Internal Return Rate (IRR) financial indicators will be obtained for each supply chain alternative. This will give the possibility to compare the supply chains not only operationally but also financially.
3. Arctic weather conditions & Stakeholders

This chapter describes the characteristics of the Arctic climate which affect the logistics activities. Strategic planning is challenging as the time window available to perform jobs is very limited and hard to predict.

On the other hand, an introduction to stakeholders and their interests in the Arctic help in the preparation for any future approach.

3.1. Arctic characteristics

3.1.1. Description of the Arctic

The Arctic is defined as the Northern hemisphere region located within the Arctic Circle. This area within the Arctic Circle is the latitude where sunlight is present or absent for 24 continuous hours during the summer and winter solstices, respectively. Alternatively, it also consists of the area where the average temperatures during the summer months are below 10 °C. The Arctic area represents approximately 6 percent of the Earth's surface; one third of it is land, one third consists of offshore continental shelves with no deeper than 500 meters Ocean water and the last third is Ocean water deeper than 500 meters. (U.S. Energy Information Administration, 2009)

As can be seen in Figure 3.1 the Arctic jurisdiction contains eight countries: Canada, Denmark (Greenland), Finland, Iceland, Norway, Russia, Sweden, and the United States (Alaska). From these countries, only Finland and Sweden do not border the Arctic Ocean and therefore have no claims in the Arctic Ocean or its adjacent seas. (U.S. Energy Information Administration, 2009)

The Arctic Ocean is mainly surrounded by the following Arctic seas:

- East Siberian Sea
- Laptev Sea
- Kara Sea
- Barents Sea
- Norwegian Sea
- Greenland Sea and Denmark Strait
- Davis Strait, Baffin Bay and the Nares Strait
- Hudson Bay and Hudson Strait
- Beaufort Sea
- Chukchi Sea
- Bering Sea and Bering Strait
Access to the Arctic Ocean is limited to four main channels as indicated in Figure 3.1:

- 1. Chukchi Sea between Russia and Alaska via the Bering Straits
- 2. Baffin Bay, Davis Strait and Labrador Sea between Greenland and Canada
- 3. Greenland Sea between Greenland and Svalbard (Norway)

In this section a location in the Arctic area is given, to position the focus of the project. Not only the remoteness of the area should be considered for this case, certain weather conditions are typical for Arctic and will be described in the following section. Both items will affect a logistic operation and therefore a notion of these conditions should be given.

### 3.1.2. Arctic weather conditions

The Arctic area has extreme weather conditions: winters are long and cold and summers are short and cool. All regions experience extremes in solar radiation (high in summer and low in winter) in both season and ice could be the main common denominator for most of the year whether its sea ice, glacial ice or snow. In general the extreme cold, darkness and low visibilities are all factors that can bring an impact in the performance of logistics operations. Below a short description of some of these conditions is given.
Sea Ice

As ocean water freezes it becomes sea ice. Sea ice forms, grows and melts in the ocean. Other types of ice formations like icebergs, glaciers, ice sheets and ice shelves are formed on land. As sea ice is being formed it is classified by the development stage that considers both thickness and age. If classified by age, then sea ice can be named first year ice which occurs during its first winter of life and melts again during the summer period. If a first year ice survives the summer and continues its growth becomes a second year ice or could become multiyear ice if it survives more than two summers.

The terminology used in this report is based on the classification found in The National Snow and Ice Data Center:

"New ice refers to ice less than 10 centimeters thick. As the ice thickens, it enters the young ice stage, defined as ice that is 10 to 30 centimeters thick. Young ice is sometimes split into two subcategories, based on color: grey ice with 10 to 15 centimeters thick and grey-white ice ranges between 15 to 30 centimeters thick. First-year ice is thicker than 30 centimeters, but has not survived a summer melt season. Multiyear ice is ice that has survived a summer melt season and is much thicker than younger ice, typically ranging from 2 to 4 meters thick." (National Snow and Ice Data Center, 2011)

Sea ice is in constant movement except for ice attached to coastal regions or shallow areas, this is called fast ice. The motion of ice is induced by factors of wind, ocean currents, coriolis force (rotation of earth) and ice stress forces.

Drifts and currents

Currents and wind are the main driving forces of the ice movement or ice drift. As wind blows the results is the dragging force over the sea ice surface, consequently making the ice drift. The force in the movements will depend on the speed of the wind and if the surface of the sea ice is rough or smooth. In the opposite direction of the wind, ocean currents typically act as a drag on the sea ice motion driven by wind.

Temperatures

Due to the location of the Arctic, the received solar radiation is already less intense compared to the tropics. Also in this high latitude the sunlight during the winter period is not existing and on the contrary continuous during the summer. This leads to eternal nights or days period accordingly.

Temperatures in Arctic are directly related to the incoming solar radiation over the course of a year as can be seen in Figure 3.2.
The impact of the climate factors on the logistic operations and activities in the Arctic mentioned below are based on experience gathered by Shell in similar conditions with earlier projects. Table 3.1 shows some typical risks related to Arctic operations and their possible mitigation measures:

<table>
<thead>
<tr>
<th>Arctic Conditions</th>
<th>Risk Description</th>
<th>Recommendations</th>
</tr>
</thead>
</table>
| Low air temperatures   | For workers it is difficult to perform work in winter season when the wind speed, wind chill factors and air temperature becomes excessively cold and drop below defined parameters.  
It reduces work efficiency dramatically and work often has to be stopped to allow men to get warm.  
Some construction operations cannot be done due to low temperature impact on materials being used.  
Impact on marine operations as ice accumulation on ship structures from spray or fog can be severe; it may add weight to vessels and requires to be removed. | Adverse weather policy is required to advise on Personal Protection Equipment and when not to work, as wind chill factor increases.  
Consideration must be given to winterize (protection of equipment against ice formation) the work site to enable protection from the cold and wind.  
Winterization of vessels is required by law in the majority of the Arctic area. |
<table>
<thead>
<tr>
<th>Arctic Conditions</th>
<th>Risk Description</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offshore waves with ice</td>
<td>Road accidents due ice or malfunctioning of equipment in response to low temperatures.</td>
<td>Vehicles need to be tracked and journey management is a key safety process. Vehicles need to be fit for driving over different terrains, always have adequate survival equipment and be tracked at all times.</td>
</tr>
<tr>
<td>High winds</td>
<td>Delays to offshore work, affects offshore operability, impact on shipping and offshore logistics. Impacts helicopter operations, vessel loading and offloading, Air Cushioned Vehicle operations, and cranes</td>
<td>Vessels must be ice class and of the appropriate ice class for tasks to be carried. None ice class vessels will be restricted to summer open water season only. Essential to have good ice forecasting and modeling capability coupled with Metocean models but always up to date observations will improve the selection of the route. Require experienced Metocean and Ice Specialist to develop models and forecasts. Require Ice Code to determine when to evacuate offshore locations. Require Adverse Weather policy to cater for these needs. May impact Emergency Evacuation Response activities as well and may have to consider parameters when to shut operations down.</td>
</tr>
<tr>
<td>Arctic Conditions</td>
<td>Risk Description</td>
<td>Recommendations</td>
</tr>
<tr>
<td>-------------------</td>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Sheet ice and floes (sea ice)</td>
<td>Impact on offshore mooring, facilities, subsea and drilling equipment. Impacts logistics support and shipping.</td>
<td>May need to develop convoy concept to deliver materials, equipment and personnel offshore. Convoy consists of Icebreaker to create channel, Icebreaker beam must be wider than following vessels. Following vessels can be ice class Supply Vessel or ice class barge and or ice class Push / Pull tug. Require Ice Class Stand by Vessel offshore location. Need Icebreaker to keep area around offshore location open for product and re-supply movements. Offshore location will need ice protection structures built of rock, or barges made of steel or concrete, or old vessels which can be sunk. Rock is a permanent solution. Barges which can be sunk must be able to re-float so can be repositioned as more experience is gained. Ice Protection Structures needed to be positioned to protect on most common wind direction in the area. It is the wind force which pushes the ice floes and sheets. The Ice Protection Structures need to be positioned with great care to allow sufficient space for vessel movements inside the zone.</td>
</tr>
<tr>
<td>Fog</td>
<td>Negates or reduces helicopter operations. However marine and Air Cushioned Vehicle activity can continue but under less speed.</td>
<td>Good radar is required and communication system supported by a Vessel tracking system from a land based location. Road driving may need to be restricted or forbidden</td>
</tr>
</tbody>
</table>
### Arctic Conditions

<table>
<thead>
<tr>
<th>Arctic Conditions</th>
<th>Risk Description</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Darkness</td>
<td>24-hour darkness during winter months; impacts on construction, logistics and maritime activities.</td>
<td>A policy is required to be set for Logistics operations so that core work activity is done in normal bio work time i.e. 0600 to 1800, irrespective of season. Flying rotary craft and driving should not be done outside that time, unless it's an emergency, an evacuation or potential loss of asset. Marine vessels in transit are not affected but docking and quayside operations both on and offshore are activities recommended to be done in the core time.</td>
</tr>
</tbody>
</table>

As described, Arctic is a difficult area to perform work. Many risks should be considered due to the different climate characteristics, consequently mitigations should be in place as for some cases it was explained in Table 3.1. It can be concluded that operations in Arctic are focused on control and up to date observations. This will lead to a good deployment of scheduling and safe operations. Further details on the climate characteristics and geographic conditions will be described in the following section to have an overview of the nature of representative seas in the Arctic.

### 3.1.3. Description of weather conditions for main Arctic seas

The characterization of the Arctic seas has a very important purpose for logistics in Arctic. With an overview of what to expect from the weather conditions, planning over scheduling and opportunities that can be used in order to improve or utilize elements of a supply chain differently can be better assessed. The final idea from such knowledge would be to be able to create a plan for the typical year for the seas on what to expect weather wise and which activities can or are not possible to take place.

The most representative seas will be described and an example of what could be detached from this information will be given at the end.

1. **East Siberian Sea:**

| Wind | Winds are unstable between November to March. In spring, (April – May) the number of cyclones ranges from to one or two and then July increase to four or five. Storms with mean wind speed lower than 15 m/s at the coast are observed between 15 to 50 days per year. In summer, the maximum wind speed usually does not exceed 22 to 24 m/s in the western region and 28 to 30 m/s in the east. |  |
### Air Temperature

Air temperatures below 0 °C are observed during the major part of the year over the sea. The duration of the period having positive daily temperature is less than two months in the north and three to three and half in the south. In the summer the highest temperature doesn’t reach higher than 15 °C in the northern half and 25 to 30 °C near the coast.

Coldest months are January and February.

### Waves and Currents

The value of the tidal variation in sea level for a large part of the sea does not exceed 0.3 m while the wind fluctuations can reach 2 to 3 m or more.

In the northern part of the sea, the permanent current coinciding with the main Trans-Arctic drift is directed towards west-northwest. In the eastern part, an easterly costal current is observed.

Waves are relatively low due to significant ice cover and the shallowness of the sea. In July to October, as the ice edge moves northward, the frequency of occurrence of high waves increases, reaching its maximum in September.

### Water depth (m)

Very shallow water basin with extremely flat bottom sloping to the northeast. Prevailing depths ranges from 10 to 20 m in the west and from 30 – 40 m in the east.

### Ice conditions

October to May/June, the sea is entirely covered by sea ice. Ice growth lasts until the end of May. The ice cover (both Land-fast and drifting) at the beginning of the melting consist of thick (more than 120 cm) first-year ice and occupies about 80% of the sea surface in the western part and about 65% in the eastern one. The other 12% and 30% consist of multi-year ice respectively.

Small icebergs, floe-bergs and ice islands occur.

During July to September the ice cover finally melts becoming open water sea. By the first week of October first young ice starts to appear at the north and slowly moves southward.

### 2. Laptev Sea:

#### Wind

Variations in depression between ocean and land weather lead to sharp fluctuations of air temperature, strong winds, cloudiness and precipitation.

Weak winds of less than 5 m/s prevail over the sea, but the number of days with stormy winds mayor than 15 m/s is about 40 to 50 days per year.

#### Air Temperature

In summer, the air temperature over a large portion of the sea is close to 0 °C. In the south, just near the coastline, the air temperature in July to August reaches 8 °C, but the wider coastal zone of the sea, it decreases rapidly to 2 °C. In the summer, the highest values of the air temperature do not exceed 12 to 15 °C in the north and 26 to 28 °C in south.
| Waves and Currents | Tidal wave reaches the sea from the north, steadily attenuating and changing its form as it propagates to the coast. The tidal amplitude is generally about 0.5 m and exceeds 2 m. Wind induced surges are specially significant in the summer and autumn periods, with heights reaching 2.5 m at times. Waves depend on open water areas. During the summer the highest waves caused by easterly storms wind can reach 5 m. The stormiest period is autumn (September to October). |
| Water depth (m) | There is great contrast of depth in this sea. Southern part averages do not exceed 10 to 25 m while the northern passes between 2000 and 3000 m. Still 54% of the sea is less than 50 m deep. |
| Ice conditions | From October and for nine months ice covers the entire area. Due to the peculiarities if the atmospheric circulation, ice moves northward to the Arctic Basin during most of this period. In winter (October – March) about 280000 km² of ice in average is transported from here to the Arctic Basin. Long term average for ice cover is March. Land fast ice cover more than half of this region with thickness bigger than 2 m. ice melting begins in June until final breakup of Land fast ice in July to start coming back in September. Some small icebergs occur mainly in the western part. |

### 3. Kara Sea:

| Wind | In winter storm mostly produce westerly, southwesterly and southerly winds. In summer, storm results in northerly and northeasterly winds accompanied by an air temperature drop. |
| Air Temperature | Air temperature is consistently below 0 °C for eight months starting in October. The coldest period is December to March with a mean temperature between -14 to -26 °C. The summer lasts only 4 months starting in June with a mean temperature of 7 °C. |
| Waves and Currents | In shallow areas, wind-driven currents prevail but have variable directions and speed. In general the gradients and tidal currents are weak. Tidal sea level oscillations are not greater than 0.5 m while the wind-driven surge water rise in the coastal areas can be 2 to 3 m. |
| Water depth (m) | Mean depth 111 m and maximum depth 600 m. |
| Ice conditions | Land-fast ice is established annually along all mainland and island shores. In winter there is strong ice pressure forming ice ridges which could measure up to 15 m height and 20 m keel. Icebergs are mainly centered near the northeast coast of Novaya Zemlya and the west coast of the Severnaya Zemlya archipelago. Icebergs have not been sighted in the southern coastal areas. |
4. Barents Sea:

<table>
<thead>
<tr>
<th></th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wind</strong></td>
<td>Dominant wind direction in winter is Northeaster for the Western Region of the Sea and Southeastern for the Northeastern Region. For the summer the direction changes to West and Northwestern respectively. Gusts can equal 40 m/s in the western part of the sea and 42 m/s in the central part.</td>
</tr>
<tr>
<td><strong>Air Temperature</strong></td>
<td>Mean annual air temperature varies from +2 °C in the southern sea areas to -10 °C in the north of the sea. The full range can vary between 10 °C and -39 °C.</td>
</tr>
<tr>
<td><strong>Waves and Currents</strong></td>
<td>Oscillations in sea levels change between the sea regions. In the western region wave high can reach between to 2 to 10 m height and currents with maximum speeds of 65 cm/sec. For the Northeast side the values range in similar number from 2 to 9 m height.</td>
</tr>
<tr>
<td><strong>Water depth (m)</strong></td>
<td>From 100 to 600 m.</td>
</tr>
<tr>
<td><strong>Ice conditions</strong></td>
<td>Ice cover changes mainly in the southeastern region, reaching up to the Pechora Sea between October to July and summer season can occur during August to September. West and Northeastern region is predominantly covered by ice. The highest ice cover is between March to April for 55 to 60% extension of the sea with an approximate thickness up to about 3 m.</td>
</tr>
</tbody>
</table>

5. Greenland:

<table>
<thead>
<tr>
<th></th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wind</strong></td>
<td>Intensity of pressure systems is greatest in winter. South of Greenland is particularly influenced by severe weather related to the north Atlantic winter cyclones. The maximum wind speed in the northernmost part occurs in October – November, elsewhere in mid-winter. Gale-force winds (above 13.8 m/s) are predominant in the south up to 30% chance in winter and 4% during the summer</td>
</tr>
<tr>
<td><strong>Air Temperature</strong></td>
<td>The west side has a mean air temperature below 10 °C year round. The coldest month is February and in contrast the warmest is August. In the north temperature change range can be as large as 30 °C and the south is 10 °C. It might occur in the summer to have freezing temperatures and fog (increased frequency in May to peak values in June/July and start reducing after August)</td>
</tr>
<tr>
<td><strong>Waves and Currents</strong></td>
<td>Significant wave height reaches up to 7 m in average annual value.</td>
</tr>
<tr>
<td><strong>Water depth (m)</strong></td>
<td>In average water depth is 1100 m.</td>
</tr>
<tr>
<td><strong>Ice conditions</strong></td>
<td>Northern part has sea ice much of the year. Icing caused by sea spray is frequent from November to April and rare in October and May. First ice occurs in January and last ice generally is in May. Level of</td>
</tr>
</tbody>
</table>
Ice if predominantly first-year type and even turning into Land fast ice. Icebergs are a big risk in the Greenland area with frequency present all year round.

6. Baffin Bay and Davis Strait:

<table>
<thead>
<tr>
<th>Wind</th>
<th>5 m/s in the northern regions to up to 10 m/s in the southern regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temperature</td>
<td>4 °C in August to -24 °C in February</td>
</tr>
<tr>
<td>Waves and Currents</td>
<td>Annual average wave height ranges between 7.9 – 4.1 m.</td>
</tr>
<tr>
<td>Water depth (m)</td>
<td>From 100 to 400 m.</td>
</tr>
<tr>
<td>Ice conditions</td>
<td>Ice cover: October – July</td>
</tr>
<tr>
<td></td>
<td>Iceberg source area (Approximately 2000 per year) mostly forms</td>
</tr>
<tr>
<td></td>
<td>between November - March</td>
</tr>
</tbody>
</table>

7. Beaufort Sea:

<table>
<thead>
<tr>
<th>Wind</th>
<th>The dominant wind direction ranges from the northeast to southeast during any month of the year. Southerly winds are rare during the summer. Half of all strong winds with speed exceeding 14 m/s are from the west or northwest and these winds are responsible for the multi-year ice intrusions into the coastal waters. Easterly storms are characterized by strong winds of long duration. Westerly storms are associated with extra-tropical cyclones that track from west to east or northwest to southeast across the Beaufort Sea. Usually these storms are of relative shorter duration than the easterly ones</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temperature</td>
<td>The annual ranges as maximum between 10 to 30 °C and the minimum between -20 to -40 °C</td>
</tr>
<tr>
<td>Waves and Currents</td>
<td>Extreme wind, wave and surge conditions occur during autumn storm prior to freeze-up. These are related to the description in the wind characteristics. Wave height in average reaches 3.7 m and tidal changes are not very significant.</td>
</tr>
<tr>
<td>Water depth (m)</td>
<td>Water depths range from 2 up to 90 m around the continental shelf at the mouth of the Mackenzie River, but other areas can reach to several thousand meters.</td>
</tr>
</tbody>
</table>
Ice conditions

Ice covered season begins in early October (already forming first-year ice stages) to late July, then open water season last from August to early October. Open water route doesn’t develop until the first week of September.

Ice condition can be subdivided into three regions:

Arctic Polar Pack: Composed by old or multi-year ice with level ice thickness up to 4.5 m to 5 m and ridges of 25 m thick. Continuously circulates with the current and winds and is present year round.

Seasonal shear zone: Is the extension between Land-fast ice to the edge of the moving polar pack ice. The width of this zone can vary from a few kilometers to over 300 km, both within a yearly season. It consists of mainly first year ice, but second or even multi-year ice could be found. It is a dynamic zone and can move between 3 km/day to 13 km/day.

Land fast ice zone: Is an extensive zone and can form out to a water depth of 20 m. The sheet begins to grow over late September to mid-October until it reaches its maximum thickness of approximately 1.9 m in average by April. In June the melt down begins once more.

The biggest risks in the region are Ice Island and multi-year hummock fields. These are of glacial origin and can be of sizes as big as 697 km² and thickness reaching up to 60 m.

<table>
<thead>
<tr>
<th>8. Chukchi Sea:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
</tr>
<tr>
<td>Air Temperature</td>
</tr>
</tbody>
</table>
Waves and Currents | Tidal currents do not exceed 10 to 20 cm/s in the open sea and increase slightly in the bays and gulfs. Wind caused fluctuations of sea level are significant and range from 2 to 3 m in the coastal zones. The maximum sea level fluctuations due to wind are connected with storm transits. As the open water period generally start in June to July time frame and last through October, the highest waves are observed in September through the beginning of October.

Water depth (m) | The Chukchi sea is predominantly a shallow sea.

Ice conditions | From November – December until May – June, the sea is entirely covered by ice. Predominantly first-year ice with 120 to 140 cm thickness and some concentration of multi-year ice for portions of the sea.

Land fast ice could be found in less deep waters with extension that varies among 5, 20 and 40 km from the coastal line.

Ice decay begins in mid-May and by the end of June all Land fast ice is gone. September is open water mainly. Late October ice formation starts along the Russian coastline and progresses steadily to the south until full coverage by mid-November.

Current climate changes have delayed the freeze up of this sea and complete ice cover didn’t occur before December.

---

9. Bering Sea:

Wind | Severe storms in autumn and winter.

Wind speeds are lowest in June and July with average speed around 6 m/s. Wind speed increases through the fall and by November average greater than 10 m/s. In March and April, speed starts decreasing again.

Wind direction in the winter is generally coming from the north and northwest in the northern Bering Sea, while southern regions have a fairly evenly distributed direction as well as in the summer.

Air Temperature | Winter air temperatures are generally warmer in the southwest and colder in the ice covered regions of the northeast. The variation could be as for example in December the minimum temperatures are -4 °C to -6 °C in the southwest and -38 °C to -40 °C in the northeast. Maximum air temperatures are highest in July to August when temperatures of 12 °C in the Central Bering Sea and up to 20 °C in coastal areas.

Waves and Currents | Mean wave height from May to August is less than 1 m but starts to increase in September up to greater than 2 m in November until March when the decline begins.

Tidal range is less than 0.6 m but some areas could have a difference of almost 5 m.

Currents are generally north to south due mainly to northerly winds.
Is composed of a northeastern shelf with water depths shallower than 200 m and a deep basin in the southwest with water depths greater than 3000 m.

Ice begins forming in northern coastal region in October and by November sea ice starts to grow in the northern offshore region. Its maximum extend is reached by late March. In middle to end July the Bering sea is entirely ice free. The ice is most of first year ice characteristics as it is all melted away during the summer periods. And because there are no glaciers in the area, icebergs are not a concern in the region. The presence of fog increases from the ice covered periods when it is rarely found from July to August, when 10 to 15% of all observations report visibility of less than 1 km. In September fog presence start decreasing again to allow the beginning of ice formation.

The details on Arctic seas conditions described in this section were obtained from ISO 19906 - Petroleum and natural gas industries - Arctic offshore structures and from "Comparison of the physical environment of some Arctic seas" (Løseta, et al., November 1999).

This information shows that each sea in the Arctic area has different characteristics and weather conditions around the year. This makes it difficult to be able to generalize and to predict for example ice occurrence in one area based on information taken from another area. Therefore each project in the Arctic requires specific research on the marine and weather conditions.

The importance of this chapter lays in understanding how weather conditions will affect logistics operations. Appreciating a view of the time windows available between season and their characteristics will help to create a planning tool for allowed, limited or restricted operations accordingly. As recommended by the Logistics Department within Shell a matrix describing conditions can be made and from there activities will be controlled and plan for a yearly schedule as can be seen in Figure 3.3.
The figure above shows how one season is affecting the next one by different weather factors that are impacting logistics in speed and even complete restrictions of mobility (also no complete "open window" for unrestricted operations). Each arrow represents an item that could affect movements, being ice, darkness, animal migrations, et cetera. For more details in this example, please refer to Appendix I.

3.2. Shipping in Arctic

Sailing in Arctic waters demands certain characteristics over the vessels. These characteristics are meant for the correct operation as well as maritime mandatory regulations. The main requirements will be described as an overview of Arctic shipping operations.

3.2.1. LNG Shipping in Arctic

To perform LNG Shipping the LNG Carriers (LNGC) are specially designed tankers to carry large amounts of LNG for long distances. These ships have insulated tanks able to contain the LNG at its -162 °C. In order to be able to operate in Arctic, the LNGC require strengthen hulls, icebreaking technology and in some cases assistance from Icebreakers for areas of ice thickness they can't handle.

Part of this ship strengthening and adaptation to Arctic is known as winterization and can be done in different levels. In general winterization considers strengthening the hull, utilization of special structural materials, increased engine power for enhanced propulsion and special steering systems, outside heating, icing protection for deck equipment, etc. All of these requirements are defined depending on the vessel's ice class, which depends on legislation, designed operational ice conditions and the operational mode of the ship. The rules apply for the blue area shown in Figure 3.4. There are defined rules on what a vessel with a determined ice class is allowed to do in legislation terms and what it can do in technical terms to safely operate under ice conditions.
3.2.2. Ice Class Regulations

Depending on the ice conditions the classification for ice class rules are divided into various levels. The levels depend on ice thickness, therefore as ice becomes thicker more strength and power is required by the vessel to sail. Next to that the operational profile for independent navigation or escorted by an icebreaker in a convoy navigation and the different ice conditions of drifts, ridges, concentrations, etc.; will also play a role in this classification.

The International Maritime Organization (IMO) 'Guidelines for Ships Operating in Arctic Ice-Covered Waters' are designed for Arctic conditions only (mostly the highlighted are in Figure 3.4). They establish standard points required on construction, equipment, operational and environmental provisions with special consideration for the risks of navigating in ice covered waters. On the operation side, they are based as mentioned before on limited icebreaker assistance and hence, based on an interaction scenario of a glancing impact with an ice floe. As a general view of what an example of a classification looks like, Table 3.2 presents the characteristics of navigation according to Russian Maritime Register of Shipping (RMRS) ice classification:
In Table 3.2 the different Ice Class Vessels and their capabilities of ice navigation go from LU 1 (lowest ice protection) to LU 9 (highest level). There are typical speeds expected for each class depending on the way they would operate with either an Icebreaker assisting escort or independent navigation. Safety distance assurance is the reason on the difference for lower speeds when there is Icebreaker escort and following ships in convoy configuration. In cases of convoy operation the possibilities of sudden stop due to heavy ice requires a slower navigation speed to be able to stop during emergencies. These tables are used as reference only as part of the classification made for the Ice Class Rules. It can give an idea of what could be the navigational behavior of a vessel with certain ice protection. The numbers given in the table are an indication of what each ice class should be able to handle sailing over ice covered waters. The ice class will determine the possibilities for certain vessels to travel in different location in Arctic as will be described below.

Additionally the RMRS provides guidelines for navigation depending on different Arctic regions mentioned earlier. As a vessel holds a certified ice class, it will be allowed to operate in certain conditions and seas, depending on the season. Table 3.3 gives a detailed example for the main Russian Arctic seas. Depending on the season and the ice sea conditions, an ice class vessel will be allowed to perform its trip accordingly.
### Table 3.3: Ice regulations for yearly seasons (Bridges, Hasolt, Kim, & Riska, 2004)

<table>
<thead>
<tr>
<th>Ice Class</th>
<th>Ice Operation</th>
<th>Summer - fall</th>
<th>Winter - spring</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Barents Sea</td>
<td>Kara Sea</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E x H M E a</td>
<td>E x H M E a</td>
</tr>
<tr>
<td>LU 4</td>
<td>IIN</td>
<td>+ + + +</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>IEN</td>
<td>+ + + +</td>
<td>+</td>
</tr>
<tr>
<td>LU 5</td>
<td>IIN</td>
<td>+ + + +</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>IEN</td>
<td>+ + + +</td>
<td>+</td>
</tr>
<tr>
<td>LU 6</td>
<td>IIN</td>
<td>+ + + +</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>IEN</td>
<td>+ + + +</td>
<td>+</td>
</tr>
<tr>
<td>LU 7</td>
<td>IIN</td>
<td>+ + + +</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>IEN</td>
<td>+ + + +</td>
<td>+</td>
</tr>
<tr>
<td>LU 8</td>
<td>IIN</td>
<td>+ + + +</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>IEN</td>
<td>+ + + +</td>
<td>+</td>
</tr>
<tr>
<td>LU 9</td>
<td>IIN</td>
<td>+ + + +</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>IEN</td>
<td>+ + + +</td>
<td>+</td>
</tr>
</tbody>
</table>

**Ex, H, M, Ea**

- Independent Ice Navigation
- Icebreaker Escorted Navigation
- Impermissible service
- Service with increased risk of damage
- Permissible service

- Extreme, Hard, Medium and Easy navigation
Related to the operation, the utilization of icebreakers could be required under some conditions. Icebreakers serve the especial purpose of navigation through ice covered waters by meeting three characteristics: strengthened hull, ice clearing shape and power to break and push through the ice.

3.2.3. Why is ice management and ice breaking support needed?

The objective of traditional ice transit operations is to maximize transit efficiency by intelligent navigation and by focusing on ice avoidance and specifically avoiding the need to penetrate the most severe ice features. This results in the most efficient performance transiting from point A to point B in ice covered waters. Sometimes not only planning the route is enough for Arctic shipping and therefore specialized ice operations are required. These specialties are covered in the term of ice management.

Ice management covers the whole range of activities associated with ice detection, ice forecasting, ice breaking and ice clearing, as well as the operational decision-making process. Ice detection and ice forecasting can be referred to as passive ice management since you only observe and predict the ice without active intervention such as ice breaking and ice clearing. The main objectives are usually to increase or extend the operational window and at the same time to ensure safe operations around sea ice. The way this is done depends on the operation that requires the ice management, the available ice-breaking capability, and the ice conditions.

For shipping ice breaking is required in cases where the cargo vessels are not able to transit through the ice. As mentioned before, there are special characteristics and levels of icebreaking vessels, also different ways to operate and break the ice. Icebreaking capable ships in general have strengthened hull, ice clearing shapes and more power to push the vessel through the ice covered water. Such ships are used to keep and have routes navigable over ice-covered waters. There are two different purpose icebreakers, specialized to break ice and assist other vessels or cargo vessels with ice strengthened designed to withstand ice without having the assistance of traditional icebreakers.

For the ice-strengthen cargo vessels the principle is that they are able to navigate independently according to their ice classification and regulations. Unfortunately this is not always the case and in some occasions additional icebreaking assistance could be required. The problem is that there is not a lot of experience in this field and also limited amount of information can be found in the literature. The result is that there are no expectations on what the performance of an ice class cargo carrier with certain characteristics traveling through can be. On the same page, no information over when would additional icebreaking assistance would be required and how best to use it. In this sense, only hypothesis can be defined.

3.3. Arctic stakeholders

The objective with this chapter is having a view of what is the current political situation in Arctic, organizations involved that have regulations to protect the region and understand what could be some of the requirement necessary to operate for logistics activities in the area. With this overview a ranking can be done over stakeholders within importance and influence over Arctic matters.
Arctic Political concern

Currently the Arctic region is of focused political and economic interest. None of the countries surrounding the Arctic Ocean can claim the North Pole and they are limited to a 370 kilometers entitlement as exclusive economic zone around from their coast line. The Law of the Sea from the United Nations Convention allows country members to claim an extension to this limit area and increase it to sectors that are considered to be part of their territories as Figure 3.5 shows the limitation areas from the shore onwards. Canada, Denmark, Norway and Russia have subscribed to this law.

To understand better how the boarders are being established in Arctic, Figure 3.6 shows the limitations (boarders) each country is allowed to have and the claims they have made over the 370 kilometers boundary.

Arctic Stakeholders

The definition of stakeholder refers to persons, groups or organization that should be taken into account for all types of project development. Keeping the borderline discussion above, not only governmental institutions but also private organizations have separate coverage in their influences and interest in Arctic. In the following section a description regarding these organizations is presented. The objective is to have an overview of who could be strategic stakeholders to consider for an eventual Arctic Operation. Not all organization will be analyzed in this case as they might change among the countries.
Figure 3.7 presents a list of most important generic stakeholders classified on their concern (interest) and success criticality (power) to a project development. They are also colored in red, orange and green to determine if they are in general terms: against, mixed - neutral or in favor of development of Oil and Gas production projects – and therefore a possible LNG Logistics case. Making an early approach to these parties is considered to be helpful in an eventual implementation phase of the project:
An example of how to use a matrix to classify the stakeholder is shown in Figure 3.7. The concern is assessed by how much involved and affected will the stakeholder is around an Arctic project. An the criticality of the stakeholder is determined by the how much it could affect the success of the project.

Following this idea, main strategic stakeholders are:

1. Arctic Council

The Member States of the Arctic Council are Canada, Denmark, Finland, Iceland, Norway, the Russian Federation, Sweden and the United States of America.

Its objectives include monitoring, conservation, emergency preparedness, sustainable development and elimination of pollution. The Arctic Council supports six different working groups:

- Arctic Contaminants Action Program (ACAP)
- Arctic Monitoring and Assessment Program (AMAP)
- Conservation of Arctic Flora and Fauna (CAFF)
- Emergency Prevention, Preparedness and Response (EPPR)
- Protection of the Arctic Marine Environment (PAME)
- Sustainable Development Working Group (SDWG)

Each working group has a specific mandate to operate and it is their own responsibility to execute programs and projects mandated by the Arctic Council Ministers. (The Arctic Council, 2007)
2. International Maritime Organization (IMO)
IMO was established by a UN Convention “to provide machinery for cooperation among Governments in the field of governmental regulation and practices relating to technical matters of all kinds affecting shipping engaged in international trade; to encourage and facilitate the general adoption of the highest practicable standards in matters concerning maritime safety, efficiency of navigation and prevention and control of marine pollution from ships” (International Maritime Organization, 2011). Some specific interest over these stakeholders is given as IMO has published guidance on vessels operating in Arctic waters, which is one of the main concerns when studying a Logistics Project for LNG in this area.

3. United Nations Environment Program (UNEP), (GRID-Arendal) Polar Program
The Polar Program of UNEP/GRID-Arendal, is UNEP's key Polar Centre. In collaboration with numerous partners and regional stakeholders, it undertakes projects and initiatives that aim to:
- Facilitate and/or participate in stakeholder processes that recognize different values, perspectives, and knowledge, with a particular emphasis on empowering Arctic peoples;
- Provide interdisciplinary polar assessments and early warning to build awareness as a foundation for decision-making;
- Provide outreach, education and communication services;
- Provide analytical and management tools, methods and expertise to meet stakeholder demands.

It is an important organization to gain knowledge of sustainability in Arctic, understand its biodiversity and acknowledge its protected areas to be in harmony with traditional lifestyles and cultures of the Arctic People. (United Nations Environmental Program: GRID-Arendal, 2010)

4. International Association of Oil and Gas Producers (OGP)
The International Association of Oil and Gas Producers (OGP) (formerly the E&P Forum) has published two sets of guidance specific to oil and gas exploration and production in the Arctic:
- Oil and Gas Exploration and Production in Arctic and Subarctic Regions – Guidelines for Environmental Protection (developed in association with IUCN);
- Oil and Gas Exploration and Production in Arctic Offshore Regions – Guidelines for Environmental Protection.
(INTERNATIONAL ASSOCIATION OF OIL AND GAS PRODUCERS, 2011)

5. International Petroleum Industry Environmental Conservation Association (IPIECA)
Since it was established, this organization addresses global environmental and social issues related to the petroleum industry including: oil spill preparedness and response; global climate change; biodiversity; social responsibility; and human health. IPIECA also helps members identify new global issues and assesses their potential impact on the oil industry.
IPIECA helps the oil and gas industry improve its environmental and social performance by:

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developing, sharing and promoting good practices and solutions
enhancing and communicating knowledge and understanding
engaging members and others in the industry
working in partnership with key stakeholders

6. The International Union for Circumpolar Health (IUCH)
The objectives of the IUCH are to:

- Promote international cooperation in circumpolar health.
- Encourage and support research and exchange of scientific information in the circumpolar health sciences.
- Promote public awareness of circumpolar health.
- Provide a means of communication with other scientific organizations.
- Promote and encourage the participation of indigenous peoples in circumpolar health affairs

They are involved in knowledge of Environmental Legacies and Liabilities that could determine the way to operate in sensible areas like Arctic. (International Union for Circumpolar Health, 2011)

7. The International Union for the Conservation of Nature and Natural Resources – IUCN
Also known since the 1990s as the World Conservation Union, IUCN is the world’s largest and most important conservation network. The Union brings together 82 States, 111 government agencies, more than 800 non-governmental organizations (NGOs), and some 10,000 scientists and experts from 181 countries in a unique worldwide partnership.

The Union’s mission is to influence, encourage and assist societies throughout the world to conserve the integrity and diversity of nature and to ensure that any use of natural resources is equitable and ecologically sustainable. (International Union for Conservation of Nature, 2011)

8. WWF Arctic Program
It is a campaigning NGO with its own well-developed Arctic Program. WWF is a well-known organization concerned on biodiversity conservation and natural resources use. (World Wildlife Fund - Arctic, 2011)

Once precise locations are defined, a stakeholder analysis should be done to verify more organizations that are important and have impact in the exact project area. This is the first step in identifying representative organizations for communities in the Arctic and which are vocal points on matters pertinent to oil and gas development in their part of the Arctic Region.

3.4. Natural resources found in Arctic
Easily available oil and natural gas resources are developed and will become exhausted in the near future. Therefore the Arctic area is explored for future oil and natural gas supply however the high cost to develop and exploit these resources would limit the feasibility of these projects. Finding large reservoirs is crucial to enable development of smaller
The large reservoirs are responsible of "supporting" the initial investment but even then the cost could be such that these fields remain undeveloped.

Figure 3.8 illustrates how the Arctic has been opened up for exploration of different mining resources. Particular areas of interest are: Barents Sea, Mackenzie Valley and the Alaskan North Slope. These are areas which are expected to hold those large reservoirs as mentioned above. In some cases, there are contrasting examples like first the "Prudhoe Bay Field with 13.6 billion barrels of recoverable oil made the construction of the Alyeska Oil Pipeline commercially viable. Without the Prudhoe Bay Field, it is unlikely that the smaller Alaska North Slope oil fields would have been developed" but in the same area there are also "35.4 trillion cubic feet (6.3 billion barrels of oil equivalent) of the discovered Alaska North Slope natural gas resources remain unexploited due to the absence of transportation infrastructure." (U.S. Energy Information Administration, 2009). This is an indication that more projects in Arctic will be developed, gradually as more investments on infrastructure is done proportionally smaller scale projects become more interesting. Nevertheless, Arctic’s difficulties have to be overcome to be able to extract oil and gas in a responsible and efficient manner to later be transported to the market.
Currently the question that should be asked is not how the exploration will be done, but when will it start.

Summary
The Arctic is not only a remote location, but also has weather conditions that can affect logistics and work operations for oil and gas extraction. Among those weather conditions principally low temperatures and ice formations impose one of the main logistics challenges of this area. Getting to know these unfavorable conditions, allows the future planning of activities accordingly. The main message is that exploration and development of Arctic will take place in the future, so controls to mitigate the impact of the weather should be in place. A careful schedule considering the different conditions around the seasons should be considered in order to facilitate the transport activities to deliver products to the market. Additional mitigation measures are in hand to make operations safer for people against ice, darkness, low temperatures, and etcetera. Finally with the expected potential undiscovered reserves of natural gas and oil, Arctic will become a very active area. Even with the challenges, taking the right measures concerning the weather it can be a successful business.

This chapter also presents an overview of the political situation to be considered when planning to develop a logistics project in the Arctic region. Definition on borders line, relations between countries, different legislations, rules and finally strategic actors and local stakeholders play in various levels over Arctic interest. Once a detailed location is defined for a project, a close analysis should be developed in order to determine a stakeholder approach. The objective will be to:

- Create an integrated strategy that aligns and leverages across all key stakeholder groups (local community, NGO, state, municipal and federal government, regulators, and private industry)
- Achieve critical stakeholder consent, neutrality of opposition, government and regulatory reform needed to facilitate the development of the projects
- Look at actions for near term, but with a view toward balancing short and longer term needs required to formulate a solid stakeholder foundation for subsequent lifecycle project phasing.

For Arctic Oil and Gas development project, stakeholder concerns include impact of climate change. Also the impact could have on the unique biodiversity and indigenous people’s subsistence way of life, industry’s readiness and capability to handle an Arctic offshore oil spill. Some environmental NGOs and indigenous organizations openly oppose Arctic oil and gas development, but Arctic countries license offshore areas for exploration and development. This is one big challenge and therefore the importance of building up the relation with active and influential parties of the Arctic.
4. LNG supply chain

One of the biggest difficulties after making a new discovery of a natural gas field is determining how to get this product to the market. As an alternative to deliver natural gas to diverse market locations around the globe, liquefied natural gas (LNG) has given flexibility and economic balance considering distant delivery locations from the production site.

Before final delivery, natural gas has to be processed first and later liquefied if needed. The process to complete the LNG supply chain will be described, along with the elements used to reach the markets and alternatives considering an Arctic production location.

4.1. Description of LNG supply chain

As mentioned before, Liquefied Natural Gas is the alternative method to transport methane from the producer to the consumer. “Methane gas is cooled down to -162°C, converting its gaseous phase into an easily transportable liquid whose volume is approximately 600 times less than the equivalent volume of methane gas.” (Chandra, 2006).

The LNG supply chain can be described as a simple logistic channel. In Figure 4.1 shows how from one individual producer will directly deal with the final customers, therefore “making the control over logistics relatively easier” (Coyle, Langley, Gibson, Novack, & Bardi, 2009). In the case for LNG, it flows directly from production to customer and no third parties are involved.

![Figure 4.1: Simple logistic channel for LNG](image)

The inbound flow starts from the upstream section of gas production at the wells. In this first stage, natural gas is extracted to be delivered to the LNG Production facility. The LNG production is performed at onshore or offshore facilities. Usually it receives natural gas from various wells in different locations. To produce LNG, the natural gas is separated in its different components and finally the gas gets cooled down until it liquefies to become LNG. The LNG is then stored in tanks until a LNG Carrier is ready to load the product from the port’s berth. These vessels will depart from the Production Port to reach a client in diverse locations and follow the process of berthing again to unload the LNG which will finally get stored in the client’s tank for further regasification and distribution into the natural gas networks or other specific needs.

For this project the LNG supply chain is considered with the structure mentioned before. Within the simulation tool to be used for the assessment of the different designs and scenarios all of these elements these stages can be programmed. Also various aspects that will impact the supply chain can be included; for the research purpose of this project only sea ice will be modeled to impact the performance of the supply chain affecting mainly the voyage duration. The possibilities to develop an LNG Supply chain under Arctic
conditions will be graphically shown in the following section. The designs are following the same process as for the LNG supply chain just described before.

4.2. Proposals for LNG supply chains concepts for Arctic

In order to have different alternatives for a supply chain scenario to deliver natural gas coming from Arctic locations, various combination and arrangements of the elements building the LNG supply chain to the demand market were considered. Therefore derived supply chain concepts are being presented, to describe the way they are composed and finally to be analyzed and selected to further continue in the simulation.

In order to identify the elements used in the graphical representation of the supply chain concepts, in Figure 4.2 a quick view of the conventions can be observed:

![Figure 4.2: Conventions for elements included in supply chain concepts](image)

Since the concepts are for a supply chain for Arctic, the gas fields are all located in an Arctic area. As described by the LNG supply chain, Natural Gas production from the Gas Fields, LNG Production, and LNG Storage will be the beginning of the chain. Then after the LNG transport, which could include the LNG Carriers in two types, one specialized for open water operation and the second one with icebreaking capabilities. For navigation support, Icebreaking vessels to assist during crossing of heavy ice in case it might be required. Pipelines are included as one of the alternative elements to transport natural gas and finally an Ice-Free Canal element which will be described later on. Some of these elements could be located within the Arctic area or partially outside the ice covered area. At the end of the supply chain, the demand Markets are included to finally deliver the LNG.

The supply chain concepts composed are the following:

1. Arctic conventional
2. Ship to Ship Transfer
3. Hub to Ship Transfer
4. Ice Free LNG Production
5. Natural Gas Only
6. Open Box

And will be described below to understand the details for each concept.
1. Arctic Conventional:

Figure 4.3: Arctic Conventional concept

In this concept the production location is considered to be within the Arctic, therefore surrounded by an ice covered area for most of the year (within the hexagon area). In this case, the LNG Carrier is considered to have a certain Ice Class to be allowed to travel on ice covered waters. In addition an Icebreaker could be used as in the occasion of thick levels of ice, it could assist in the operation of the LNG Ice Class Carrier in case this one is trapped or to improve the speed in the voyage within the sea ice covered area. Once in Open Water, the LNG Ice Class Carrier continues its voyage to deliver to a determined market location with no further impact.

2. Ship to Ship Transfer:

Figure 4.4: Ship to Ship Transfer concept

The Ship to Ship Transfer concept is in principal the same as in the Arctic Conventional concept. As seen in Figure 4.4 the production site is still inside the ice covered area, therefore LNG Ice Carriers will be used and in certain cases assistance of Icebreaker could be required. The main element for a Ship to Ship transfer is the concentration of the LNG Ice Carriers within the ice covered waters. At the edge outside the ice covered water, a
point is selected to transfer the LNG straight into an LNG Open Water Carrier. The LNG Open Water Carrier will take the cargo to the final destination in the market locations. There are some variations possible to this concept. First the variation of allowing the LNG Ice Carrier to not do the transfer into the LNG Open Water Carrier, but continue to deliver its cargo to the demand Market regardless of the season; this case would make it just as an Arctic Conventional concept. Another variation is available during the season where the ice is melted, then the ice limitation is reduced to the point where the LNG Ice Class Carrier could continue the journey direct to the market (as before explained), or the Open Water LNG Carrier could reach the Production Location. In either case the translation into an Arctic Conventional concept can be done for some part of the year. This can also be used in the advantage of allowing some vessels to go into maintenance, once another vessel could cover the full trip.

3. Hub to Ship Transfer

![Diagram of Hub to Ship Transfer concept]

The Hub to Ship Transfer concept considers a similar principle to the Ship to Ship Transfer concept. The main difference is the inclusion of a Hub (LNG storage facility) at the edge outside the ice covered water. This hub is able to store and be used as a buffer between the different vessels involved in the transfer. From the Hub, an LNG Open Water Carrier will be loaded to deliver to the market locations. In this case, the alternative of not utilizing the Hub could be considered in the situation where the ice covered waters is reduced. When the Open Water LNG Carrier could reach the Production location or the LNG Ice Class Carrier could continue the voyage to the market locations. As the vessels can reach both ends of the chain from production to markets, it can be considered as the Arctic Conventional design once more for some part of the year.
4. Ice Free LNG Production

The elements in this concept are aiming to have a Production location which is outside the ice covered area and consequently being able to use LNG Open Water Carrier and the conventional LNG Shipping through open water voyages. Taking the Production location outside the ice covered area is done by means of a pipeline construction and this implicates other considerations of the LNG Supply Chain.

5. Natural Gas Only

As the name of the concept states, for this case the utilization of pipeline to reach all the way to the market location refers to the avoidance of LNG Production. In this design, the whole focus will be on the route to follow with the layout of the pipeline and the obstacles it would need to overcome to reach long distances to one market.
6. Open Box

Keep a path open by:
- Ice free Canal.
- Big fleet of Ice-Breakers.

Figure 4.8: Open Box concept

Even though as shown in the picture above the Production location is still inside the ice covered area, the implementation of a continuously open water canal using technology development for icebreaking methodologies or innovative infrastructure design would be expected to have a Conventional LNG Supply Chain by means of an LNG Open Water Carrier to reach both Production and Market Locations.

The six concepts described are considering elements to transport Natural Gas to where demand is present. The following stage is to make an analysis of the weakness and opportunities that each concept could have in order to further investigate the possibilities for a logistics study as part of the main objective of this thesis.

4.2.1. Observations on the supply chain designs for Arctic

After discussions with various subject matter experts within the design and construction of the different elements for LNG Production, the main issues are being summarized in Table 4.1. These are a compilation summary from various interviews made during the design and proposal presentation. Please refer to the contributors list in Appendix II.
Table 4.1: Arctic Supply Chain Design observations

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Conventional Supply Chain</td>
<td>- Requirement of specialized vessels to travel through ice (Ice Classed Carriers) and Icebreakers.</td>
</tr>
<tr>
<td>- As the name states, it is conventional and the first alternative to be considered for Arctic operation.</td>
<td>- It is difficult to consider the operation of ice management, for Icebreakers during the icy season and more developments should be pursued.</td>
</tr>
<tr>
<td>- Less LNG transfers.</td>
<td>- Ice conditions are difficult to forecast, but awareness tools are in place (radars, GPS, satellite observations, etc.) to give essential support for ice operations.</td>
</tr>
<tr>
<td>- All technology considered for this concept is available and ready to be used.</td>
<td></td>
</tr>
<tr>
<td>2. Ship to Ship Transfer</td>
<td></td>
</tr>
<tr>
<td>- It allows the Ice Classed Carriers Fleet to be focused in the Sea ice occurrence area.</td>
<td>- It is a new concept being developed specifically for LNG.</td>
</tr>
<tr>
<td>- It is expected that less Ice Classed Carriers would be required as they have to travel less distance.</td>
<td>- Facilities for transferring should still be designed and constructed.</td>
</tr>
<tr>
<td>- Design of transfer systems and specialized vessels is currently being pushed on for development.</td>
<td>- Ice management and Icebreaker support would be required for the ice area.</td>
</tr>
<tr>
<td>3. Hub to Ship Transfer</td>
<td>- Shipping schedules become a big issue for on time arrivals to avoid long waiting times.</td>
</tr>
<tr>
<td>- It is a concept currently being used, but mainly on locations where storage has already been installed before and not for the purpose of distribution, but more as a business. Keeping LNG stored until prices are more attractive.</td>
<td>- New loading and storage facilities increase the investment cost and therefore economic feasibility becomes an important issue.</td>
</tr>
<tr>
<td>- The additional storage at the Hub creates a buffer between the transfer point from the Ice Classed Fleet to the Open Water one, allowing more freedom in schedules.</td>
<td>- Ice management and Icebreaker support would be required for the ice area.</td>
</tr>
<tr>
<td>- It allows the Ice Classed Carriers Fleet to be focused in the Sea ice occurrence area.</td>
<td>- Operation costs of the whole supply chain will increase with the additional terminal facilities.</td>
</tr>
<tr>
<td>- It is expected that less Ice Classed Carriers would be required as they have to travel less distance.</td>
<td></td>
</tr>
<tr>
<td>- All technology considered for this concept is available and ready to be used.</td>
<td></td>
</tr>
</tbody>
</table>
4. Ice Free LNG Production

| - No need for any sort of specialized ice fleet as it is expected to be in an ice free area. |
| - Pipeline construction in the Arctic has major challenges both onshore and offshore. Onshore the permafrost changes during the season, making the soil unstable. Many civil techniques can be used, but they are limited to distance by investment costs. Offshore there are similar challenges and also the risk of getting hit by ice grounded to the bottom floor. These considerations increase the value of investment. |
| - Distances against costs become an important issue to study the feasibility of the project. |

5. Natural Gas Only

| - Doesn't use shipping at all. |
| - Besides considering the issues of arctic pipelines, the possibility to reach already installed natural gas networks could be an option. In this case, flexibility is reduced in the possibility to reach diverse markets and a heavy stakeholder approach should be considered by crossing different borders. |
| - Limited in the distance it can deliver to according to the ratio between distance and costs. |
| - Is not using LNG. |

6. Open Box

| - The ideal would be to be able to implement Open Water Carriers for this design, but as that is not possible at least a lower Ice Classed Vessel could be used (which is expected to be less expensive) due to the minimum Arctic shipping regulations. |
| - There are different alternatives to have an open water channel in the sea, but is highly investment intensive. Besides due to regulations on Arctic shipping, the vessels would still require ice capabilities and therefore the advantages of this design would be lost. |
| - Ice conditions along any potential route that is not too confined by land masses, can change continuously due to ice drifting, ice pressure, etc. consequently any broken channel is soon lost. It is therefore usually pointless to try and maintain an open channel unless a vessel transit trough it immediately. In the case of land-fast or land-constrained ice, broken ice channels |

LNG logistics under Arctic conditions
may soon freeze over, and ice conditions can become more severe following a number of successive breaks. Channel breaking should therefore be carried out immediately before vessel transit (i.e. the escort vessel travels with the escorted vessel).
- Research over icebreaking and ice operations should be done.

Considering the points mentioned before as part of many discussions and recommendations, a decision over which concept to select should be done. The concepts to be selected will be the ones to be implemented for further simulation and analysis in this research project.

4.2.2. Selection of supply chain concepts for Arctic

The designs described in this chapter give an impression of different alternatives to consider the supply chain for LNG and final transport of natural gas to the market from an ice covered area like Arctic. For the purposes of this report the selection of concepts to be studied will be based first on the logistics aspects during operation and secondly on feasibility of the design. Therefore, the designs containing pipelines are ruled out, as these structures require specific civil design characteristics which are not going to be dealt for this report. Because of this the concepts named: (4.) Ice Free LNG Production and (5.) Natural Gas Only are taken out. For the second point, the feasibility aspect is also being included to determine which concepts to consider for evaluation. The concept named (6.) Open Box determines an open water channel available through the sea ice. As some studies have been carried out to determine that a channel of this characteristics could be feasible but only in small scale environments, it is decided that the (6.) Open Box concept is also not going to be considered for this research project. Further study will only be considered therefore on the supply chain concepts of (1.) Conventional Arctic LNG transport, (2.) Ship to Ship Transfer and (3.) Hub to Ship Transfer as their characteristics are considered to be more feasible and related to the objective of this research project.

4.3. Supply chain vulnerability to Arctic conditions

The robustness of the supply chain for LNG under Arctic conditions is part of the analysis to reach the objective of this research project. In Section 2.2 some questions are proposed to assess the vulnerability of the supply chain. Discussion points related to these questions are listed below in the case of designing the LNG Supply Chain in Arctic. Understanding how the supply chain can be vulnerable and through other means how it can become more robust is an important step for the assessments that will be made during this research project.

After discussions with experts and experience gather during the development of this project, some ideas to mitigate the consequences of a challenging environment like Arctic are described in the following points:

- No resilience for Arctic conditions is cheap as equipment and transport is expensive in materials and design and operation
• Low utilization indicators along a year’s season. If a process of transport is design for ice season, then it is expected that during no ice months there will be over capacity. On the contrary case, if designed for free ice season, lack of capacity would occur when the sea ice covers the route.

• Immediate alternative of open loop ships as a last minute resource to pick up product and deliver to customer is an option to respond to small disruptions and could give time to prepare for a long term solution. But this would be a difficult option to consider as it would be expected to not find Ice Classed vessels that comply with Arctic shipping regulations.

• Having a mixed fleet can make flexibility in Arctic Shipping. High level ice classed ships will be used during the ice months and for summer months lower ice classed ships can be used instead.

• Postponement could be a flexibility measure for LNG by means of using the storage capacity. With a smaller fleet but a bigger storage tank, production can continue and wait for better ice conditions to ship faster when reduced ice is present. In Arctic this might mean to wait for a long time, but it does help when considering lower ice seasons and then the implementation of mixed fleets for lower ice classed ships.

• Selecting critical customers is also an alternative. Serving priority customers during a year’s seasonality can also add to flexibility as demand also changes from their side. As customers service priorities it can be defined in the situation “when resources are scarce, and have intervention where it makes the maximum difference”. How to decide over this prioritization could be based on customer’s needs, profitability, cost to serve, importance for long term relations, etc.

• Control methods to assess for example if ships are on their way, if they will be on time and a clear communication scheme that can guarantee the “on time” loading and delivery of the product throughout the process

• Comparing operations of similar locations, the value of investments in security and disruption avoidance can be demonstrated between results obtained for different companies that these investments do yield in benefits that can outweigh its costs for high probability – low impact disruptions and could be less significant for low probability – high impact ones.

There will always be alternative to overcome difficulties in the Supply Chain of different products. Being creative and having enough vision, understanding and preparedness will be the differentiator between having success to deliver or being stuck with your product. Some of these points will be analyzed further in this research project; other ideas can be used as recommendations for future projects.

4.4. Description supply chain simulation tool

Now that the supply chain for LNG is described and the designs to be studied are selected, the next step is to define how the simulation will be made. To create supply chain models for LNG, Shell uses a simulation tool called SALSA – Shell’s Advanced LNG Supply Chain Application. SALSA is a simulation tool based on Flexsim environment, owned and developed by Shell and made by Talimus. Flexsim is a discrete event manufacturing simulation software and can commonly be used in the simulation of fields such as manufacturing or production lines, logistics, supply chain and distribution, traffic and transportation, among others. It has advantages of good visualization as for example 3D graphics and experimentation for some variables (Flexsim, 2011). In the simulation tool SALSA, the supply chain for LNG can be simulated by means of a production location,
a customer destination and a route to follow between those two locations. It is related to the production and storage, transport and delivery of LNG. The use of this simulation tool is to support advice and decision relating the capital investments in the logistics infrastructure for storage, port berths, fleet and commercial agreements on the delivery of LNG.

Following the process for the supply chain of LNG explained in Section 4.1, SALSA has the possibility to program these stages in detail. In addition, it can also program other events affecting the performance in the flow for the production and delivery of LNG. For example event such as maintenances, weather, port opening times, etc. The combination of supply chain elements and events taking place to affect performance makes the simulation closer to reality and therefore better to support decision making.

For this research project SALSA is the simulation tool to be used. The focus involves Arctic conditions; hence development of knowledge on how to simulate this in SALSA is required. From Figure 4.1 and according to the scope of this project, LNG Transport will be the main affected step of the flow. All elements will be included in the simulation from an example case as were generally described before, as well as how the Arctic conditions were included in the programming.

With SALSA, efficiency of the supply chain can be calculated as well as other important performance indicators as volume of LNG produced and delivered, ship waiting times, occurrence of tank tops\(^1\) or tank bottoms\(^2\) and berth occupancy.

In accordance to LNG Supply Chain, SALSA consists of a supply chain model as can be seen in Figure 4.9 with customized add-in elements to deliver functionalities related to the logistics of LNG. In the program, different variables can be set up to increase the complexity of the case, to name a couple: production capacities, flows, storage capacities, fleet size, ships capacity, port operations, distances, demand, etc. In order to perform experiments, events of weather (storms, tides, etc.), operating restrictions, planned or unplanned maintenance, fluctuations on production or demand, or factors that will have an impact over the outcomes on the supply chain and results of the simulations can be changed. The results obtained from the simulations will be analyzed based on the performance indicators important for Shell's evaluation.

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\(^1\) Tank Tops: This term relates to reaching the full level capacity for a storage tank, which obliges for production to be stop as there is no place where new product flow can be located.

\(^2\) Tank Bottoms: This term relates to the need of maintaining low temperatures (-161°C) inside the storage tanks. In case of reaching a tank bottom, the risk is to increase the temperature of the tank and therefore the need for additional processing to cool it down again before being able to perform according to the specifications.
4.4.1. Elements used in simulation tool

In detail SALSA has different elements to be able to simulate an LNG Supply Chain. An overview of these elements will be described in the following section:

Locations:

A supply chain requires a starting point to create the outbound flow. From this point products come out to be delivered to a customer. A receiving customer gets the inbound flow of the product and therefore a delivery is made. In SALSA there are a minimum of two locations: Production and Demand. Each location is different. The Production location consists of the LNG simulation processing, storage tank and a port with respective loading arms. On the other hand the demand location consists of a receiving port with berths and loadings arms to deliver the LNG, a storage tank and a demand element to consume natural gas. Within these two basic locations the first and last stage of the supply chain will take place as in one end production starts and delivery ends it. Mode details will be described in further elements that are included for each location and specific focus will be given in the Production location for the purpose of this project.

As part of the Supply Chain Designs presented in section 4.2 an intermediate location can also be included. For SALSA a Hub or a Transshipment Location can be included for the...
simulation. Even though this is a new implementation in development, already results can be obtained.

LNG Production

Within the Production Location, the LNG production behavior can be represented in SALSA. Also the production of other products can be included. The main characteristic to consider is Production Rate for a designed total. It possesses a seasonal effect due to the effect of ambient temperature (outside temperature) on the efficiency of the liquefaction process. An example to be used of seasonal production rate for LNG could have a profile as shown in Figure 4.10. A daily rate which changes according to every month (due to differences in ambient temperature) is approximated to simulate LNG production.

![Figure 4.10: LNG Production Seasonality example](image)

Storage Tank

The storage tank plays an important role in the LNG supply chain, acting as a buffer available to continue production even when the LNG Carriers are delayed. The tank is the intermediate process between the LNG Carrier’s loading and the production from the plant. As soon as the Storage Tank is full, LNG production is forced to stop. In reality, the stopping of an LNG plant implicates in restart and ramp up production, time loss and production loss. In a similar order, when the Storage Tank is empty, it “warms up”. LNG is a very cold liquid (-162 °C approximately), consequently it is of crucial importance to maintain the same temperature around the system but once an element is empty it warms up and a cool down time is required and again ends up in loss of production time.

The main characteristic to consider is Tank Size. Various Storage Tank sizes can be used to understand the implications and sensitivity this buffer has over the overall performance in LNG production and the supply chain.

Production Port – Loading Arms (Berths and Jetties)

The production port includes the port activity times and loading process. First it includes both docking and departing times for all activities vessels needs to perform before it can start to connect to load product or disconnect (using the berth and jetty). Port process of waiting in case there are no berths available, turning, mooring, etcetera are all considered in the port activities and therefore the operation time there.
Route to other locations – Legs
To link locations in SALSA, an element called “Leg” symbolizes the route between them. One or multiple legs can compose the route. Each leg will have a length defining the distance it represents.

Shipping and Fleet characteristics
This element describes the characteristics of the LNG Carriers to be used in a simulation. The principal characteristics to consider are cargo capacity, maximum speed and number of vessels (fleet size). There are other characteristics as minimum content of LNG to maintain temperature, loading and unloading rates, cooling down times (similar case as for Storage Tanks). These last characteristics can be modified of used from standard specifications.

The fleet characteristics consider besides number of vessels, the location where they are created. The vessels can be linked to the production port or the hub location.

Transshipment Location
For SALSA this functionality is recently developed. The objective of this function is to have a place where LNG Carriers can transfer LNG either to a Hub Storage Tank or have a direct Ship to Ship transfer. For both cases the same functional location as a simulation element in SALSA is used, but the difference is due to the capacity for the Storage Tank. For the Ship to Ship transfer, the LNG Ice Carriers is obliged to wait for an empty LNG Open Water Carrier to have a direct transshipment as there is no storage capacity available in between. In the contrary for the Hub to Ship concept, the LNG Ice Carrier is able to deliver its cargo and continue its return voyage to pick up more cargo, on the other side the LNG Open Water arrives to load and continue the trip to the demand market location. For either case the installations to load and unload the LNG have to be available at the port site.

For a Transshipment Location, there will be a requirement of setting up two different fleets. One will be delivering from the Production to the Transshipment Hub and the other one from the Transshipment Hub to the Market. For the purpose of this project, the same characteristics of cargo capacity and (un)loading rates are set up for both fleets (for this case an Ice Carrier Fleet and an Open Water Fleet).

The main characteristics for a Transshipment Location will be determined by the way it is being utilized. In the case of using it as a Storage Hub, the storage capacity will be the main feature. To use it as a direct Ship to Ship Transfer case, then the storage capacity is set to the lowest possible and be able to have a direct transfer between vessels. Also the location in the route can be changed, but in the case of this project it is fixed to the borderline of sea ice.

As a recent developed element, it still has room for improvement but it showed to have a behavior to deliver good simulating results.

Demand Location
The final destination and the main trigger to keep the simulation running is the demand for LNG at the customers’ location. After the LNG Carrier has loaded the product at the Production Location, “travelled” the legs, perhaps had transshipment, it finally reaches the market represented as a demand location. This Demand Location considers all Port
characteristics, duration of port activities (e.g. mooring, turning, etc.), loading rates for the loading arms (Jetties and Berths) and a Storage Tank.

Events

In SALSA the behavior of elements\(^3\) can be affected by what is called an Event. These events could be programmed either with a deterministic or a random/stochastic behavior for things like for example unplanned maintenances, schedules of port operations, tides for port entries, weather (waves, storms, sea ice, etc.). The impact of the event is set up to define how much the element will be affected in its operation performance by a certain percentage which could range on impacting its full operability – then shutting down on not being able to operate – down to a defined percentage. Also the duration can be set up and the frequency that this events are expected to occur.

For the current project the only Impact Event simulated is sea ice. The objective of identifying a robust supply chain for Arctic, indicates that sea ice will be the main player to affect the performance of the supply chain. Nevertheless, as it was mentioned in Section 3.1, Arctic holds other challenges which can be included for later stages of the study.

The mentioned elements are described as they are being used in SALSA for the simulation and study purpose of this research project. The relation of these elements is closely linked to the supply chain described in the Section 4.1 as well as the way to utilize them in order to reproduce the concepts described and selected in Section 4.2.

4.4.2. Evaluation Framework – Key performance indicators

The elements described for the simulation in SALSA, they can all be represented in the LNG Supply Chain. The characteristics are described, hence the evaluation parameters on how to compare performance of supply chains from SALSA can continue.

Performance indicators are a critical point of view for managing a business and determine if desired results are being obtained. The importance of applying KPI's to measure a business performance is better described by Fawcett and Cooper's article, where they state that 'performance measurement is critical to the success of almost any organization because it creates understanding, molds behavior, and leads to competitive results” (Fawcett & Cooper, 1998). Supply chain operations have different ways to be evaluated and eventually these results could be linked to financial performance of a project or the organization. According to Coyle et al. (2009) the characteristics of good measures are: “Is quantitative, is easy to understand, encourages appropriate behavior, is visible, is defined and mutually understood, encompasses both outputs and inputs, measures only what is important, is multidimensional, uses economies of effort, and facilitates trust. The definition of measures that indicate the performance of a supply chain for LNG will also be indicative of these characteristics and a detailed description of the main measures will be given in this section.

The LNG Supply Chain performance or capacity can be assessed basically on the Production and Delivery of the LNG. The production side is evaluated comparing the

\(^3\) As elements in SALSA, it can have an effect over single or various elements at the same time. Therefore it can affect, Production levels, Ports, Legs and therefore the vessels travelling over the route, the vessels, etc.
production level achieved against the maximum designed. In the example case to be analyzed during this research project the production from the gas supply or the treating plant is not interrupted. In contrast only between the production plant and the LNG export will be affected. To have an example, this could be affected due to restrictions on the production when there is not enough level of storage for example. The Storage Tank serves as the buffer between a continuous process of LNG production side and an intermittent process with the arrival and availability of LNG Carriers composing the fleet on the other side. When this occurs it is called a Tank Top. A Tank Top is the event of having a tank full and therefore restricting or stopping the LNG Production, this might be the consequence of a delay in a LNG Carrier’s arrival. Following a Tank Top and their frequency, the duration is also an issue to be considered. At the end these will be all indicators that can be summarized in Production Lost as a result of the LNG production being stopped.

Related to this measure, the Tank Utilization is a good indicator on the overall content present during the simulation period. In this case it will be used more as an indication, for comparison more than decision point. Once the results on Tank Tops, the distribution of Tank Levels across the time period of the simulation, can be related to the Tank Utilization, therefore an observation on the distribution of these levels can help determine the highest points of storage.

On the Shipping side, the Number of Lifts and the Number of Deliveries are stating how many parcels is an LNG Carrier loading and delivering to the client. These will be related to the route conditions and the impact over the Voyage Duration (affected mainly in the case of this project by sea ice).

Among other factors to be considered, will be the Fleet Utilization as it is an important investment made over this element in the supply chain and the highest value is what is preferred to be obtained from it.

The Berth Utilization will give an insight about the port loading activities and if the loading facilities are able to handle the fleet of carriers in each scenario run.

Comparing the behavior of these performance indicators, will be giving the point to choose for the supply chain to comply with the objective this project on finding a robust concept for LNG supply chain in Arctic conditions. The first simulations results will be evaluated considering these key performance indicators. The simulations will also be compared with a financial evaluation to determine the best return (LNG Sales) over the investment (supply chain capacity). The robustness will be determined by the level of performance of the same supply chain concept along the different scenarios determined by different sea ice conditions and finally against a variable long term variable scenario. The concepts which maintain similar performance indicators will show that are the ones who are capable of withstanding the disruptions created by the sea ice and therefore the most robust for the Arctic when considering ice.

Summary
Describing the LNG supply chain gives a better picture of the object of study for this research project. Even thought it could be considered a simple supply chain, it can be affected by diverse events and change due to the composition, characteristics and behavior of its elements. After describing six alternatives for the LNG supply chain in Arctic the selection is made for the (1.) Arctic Conventional, (2.) Ship to Ship Transfer and (3.) Hub to Ship Transfer designs. This selection is made based on experience and expectation made from experts. Regardless of thinking that this selection is the best one,
a discussion over how to make an arctic supply chain for LNG more robust is made. This increases the understanding of how the elements of the LNG supply chain can be combined to mitigate the possible disruptions to be found under Arctic conditions. The biggest concern is that at the end over capacity and therefore over spending will be the case to have for the Arctic. Finally to prepare for this, the utilization of the simulation tool SALSA will help in indicating what will be the requirements to deliver the LNG in an economically feasible project. SALSA contains the different stages and elements of the LNG supply chain, so more knowledge can be gained over what can be expected in a real situation.
5. Supply chain simulations for an Arctic example case

This chapter contains the information for the example case used to evaluate the supply chain designs selected before, some first calculations to understand the behavior of the elements and finally the implementation and results of the example case in the simulation tool used by Shell.

5.1. Introduction to example area and its shipping conditions

The scenario where the example project analyzed is taking place is in the Yamal Peninsula in northwest Russia. As seen in Figure 5.1, the area is rich in natural gas and the plans to develop these fields are going under way as stated in the Gazprom* website. This location gives challenges of Arctic conditions as have been described in chapters before (for this case the Kara and Barents Sea) and to develop a shipping route for LNG to reach the market requires careful planning. Some of these challenges are low temperatures, icing, remoteness of locations, short duration of daylight, etc. Among these the main challenge for shipping is sea ice covering the water during most part of the year. All facilities for production and transportation have to be designed to be capable of existing and operating safely in this physical environment.

* Gazprom is the largest extractor of natural gas in the world and the largest Russian company. Gazprom was created in 1989 when the Ministry of Gas Industry of the Soviet Union transformed itself into a corporation, keeping all its assets intact. The company was later privatized in part, but currently the Russian government holds a controlling stake. (Gazprom, 2003)
Routes available for the example case

From the Yamal Peninsula, there are two routes to be considered to reach the European Market of LNG: The first one Via the Kara Gate on the South side if Novaya Zemlya and further Barents Sea or a second alternative following the north of Novaya Zemlya through the Kara Sea to reach again the Barents Sea as can be seen in Figure 5.2. Both routes are indicated with 1 and 2 respectively.
Figure 5.2: Two voyage routes over the Kara and Barents Sea for year-round operation of Arctic LNG ships from Yamal Peninsula (Tustin, 2005)

The study of the ice conditions for these routes is required to determine the requirements of fleet characteristics and prediction of travel times due to ice. As it was mentioned before depending on ice thickness, vessel characteristic and mode of operation, a certain speed can be reached and therefore a travel time can be predicted. For the example case the Northern Novaya Zemlya route (Number 2) is chosen to be analyzed by the company.

5.1.1. Example case assumptions and route conditions

In order to facilitate further analysis and a more detailed study, basic project assumptions and route shipping scenarios will be defined.

Example Project Assumptions and design base

The input information is described in this point.

- LNG Production port is assumed to be located in Yamal and its production data is listed in the following table:

<table>
<thead>
<tr>
<th>Production assumptions</th>
<th>16</th>
<th>Mtpa</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNG Density</td>
<td>0.46</td>
<td>ton/m³</td>
</tr>
<tr>
<td>Production of LNG volume rates:</td>
<td>4002.71</td>
<td>m³/hr</td>
</tr>
<tr>
<td>Example Target Market</td>
<td>Europe – Spain (Bilbao)</td>
<td></td>
</tr>
</tbody>
</table>
Yamal LNG Storage and Loading base characteristics for example project are listed below:

<table>
<thead>
<tr>
<th></th>
<th>LNG</th>
<th>Condensate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank Storage [m$^3$]</td>
<td>Between 280,000 to 640,000</td>
<td>160,000</td>
</tr>
<tr>
<td>Loading Rate [m$^3$/hr]</td>
<td>10,000</td>
<td>3,000</td>
</tr>
</tbody>
</table>

The following assumptions are being used:

- LNG Production Seasonality used and approximate monthly production:

<table>
<thead>
<tr>
<th>Month</th>
<th>Impact Seasonality (%)</th>
<th>Days per month</th>
<th>Monthly Production (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>1.04</td>
<td>31</td>
<td>3,098,927</td>
</tr>
<tr>
<td>Feb</td>
<td>1.05</td>
<td>28</td>
<td>2,825,944</td>
</tr>
<tr>
<td>Mar</td>
<td>1.04</td>
<td>31</td>
<td>3,098,927</td>
</tr>
<tr>
<td>Apr</td>
<td>1.02</td>
<td>30</td>
<td>2,941,289</td>
</tr>
<tr>
<td>May</td>
<td>0.99</td>
<td>31</td>
<td>2,949,940</td>
</tr>
<tr>
<td>Jun</td>
<td>0.97</td>
<td>30</td>
<td>2,797,108</td>
</tr>
<tr>
<td>Jul</td>
<td>0.95</td>
<td>31</td>
<td>2,830,750</td>
</tr>
<tr>
<td>Aug</td>
<td>0.95</td>
<td>31</td>
<td>2,830,750</td>
</tr>
<tr>
<td>Sep</td>
<td>0.96</td>
<td>30</td>
<td>2,768,272</td>
</tr>
<tr>
<td>Oct</td>
<td>0.99</td>
<td>31</td>
<td>2,949,940</td>
</tr>
<tr>
<td>Nov</td>
<td>1.02</td>
<td>30</td>
<td>2,941,289</td>
</tr>
<tr>
<td>Dec</td>
<td>1.03</td>
<td>31</td>
<td>3,069,129</td>
</tr>
<tr>
<td>1 Year – Total Production</td>
<td>365</td>
<td>35,102,263</td>
<td></td>
</tr>
</tbody>
</table>

- The production profile from Table 5.2 is fixed for all scenarios and doesn’t change over the years.
- No boil-off is included in any of the elements.
- No darkness restriction included for Port or Shipping operation, therefore a 24 hours operation is allowed.
- No maintenance or breakdowns is being scheduled on any of the production, loading or shipping elements.

---

5 Boil-off: Small volume portion of LNG that evaporates to Natural Gas due to temperature rise, movements of liquid, et cetera, during transport or storage.
• Only Ice Impact on the route is being used, which will affect the Voyage Duration for the ships. Impact on voyage duration for simulation is a combination between the distances of each type of ice along the route with the assumed speed for the vessel over each ice type.
• Assumed speeds for vessels to cross different sorts of ice are described in Table 5.3:

<table>
<thead>
<tr>
<th>Ice types considered</th>
<th>Approximate ice thickness</th>
<th>LNG Ice Carrier Speed (knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice Free</td>
<td>Open water</td>
<td>19</td>
</tr>
<tr>
<td>Nilas</td>
<td>0-10 cm ice</td>
<td>12</td>
</tr>
<tr>
<td>Gray</td>
<td>10-15 cm ice</td>
<td>12</td>
</tr>
<tr>
<td>Gray White</td>
<td>15-30 cm ice</td>
<td>12</td>
</tr>
<tr>
<td>Thin First Year Ice</td>
<td>30-70 cm ice</td>
<td>12</td>
</tr>
<tr>
<td>Medium First Year Ice</td>
<td>70-120 cm ice</td>
<td>10</td>
</tr>
<tr>
<td>Thick First Year Ice</td>
<td>120 cm+ up to 2m</td>
<td>6</td>
</tr>
<tr>
<td>Old or Second Year</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Multi Year Ice</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Unknown ice Type</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Fast ice</td>
<td>immobile ice 'attached' to land mass</td>
<td>2</td>
</tr>
</tbody>
</table>

• No icebreaking assistance is considered within the results presented here.
• The shipping related assumptions are mainly for the selected route and speeds defined for later calculation of travel times.
• The delivery Port is completely de-bottled and has no constrains for the LNG Carriers.
• Market destination is Europe and as an example Bilbao, Spain is at 2100 nm from the ice free point selected in the route.

Production Port:
• The LNG Production Port in Yamal considers the following processing times for its activities:

<table>
<thead>
<tr>
<th>Port Steam in Processes</th>
<th>Port Steam Out Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1- Port Queue to Pilot Station [hr]</td>
<td>1- Unmooring [hr]</td>
</tr>
<tr>
<td>2- Harbor Steam In [hr]</td>
<td>2- Steam Out [hr]</td>
</tr>
<tr>
<td>3- Turning [hr]</td>
<td></td>
</tr>
<tr>
<td>4- Mooring [hr]</td>
<td></td>
</tr>
</tbody>
</table>

6 The ice types mentioned here are the ones used on the database that the MetOcean Department at Shell Global Solutions use. They indicate different ice thickness.
• It is allowed to load LNG and Condensate at the same time, but from the configuration of 1 Jetty - 2 Berth at production Port, Condensate can only be loaded from Berth 1.

Route:

- The selected route from the Yamal Peninsula to go over the north of Novaya Zemlya thought the Kara sea to reach the Barents sea and continue on open water after reaching an indication point of all year round ice free in North Cape, Russia. In order to have a more accurate description of the route, it has been divided into 10 sections called legs as shown in Figure 5.3.

![Route Diagram](image)

**Figure 5.3: Novaya Zemlya Route divided in 10 sections called legs (Shell Metocean)**

- The details of distances from legs and final destination is given in the following table:
Table 5.4: Distance of route divided in 10 sections called legs

<table>
<thead>
<tr>
<th>Sections</th>
<th>Distance [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice Leg 10</td>
<td>59</td>
</tr>
<tr>
<td>Ice Leg 9</td>
<td>82</td>
</tr>
<tr>
<td>Ice Leg 8</td>
<td>96</td>
</tr>
<tr>
<td>Ice Leg 7</td>
<td>119</td>
</tr>
<tr>
<td>Ice Leg 6</td>
<td>135</td>
</tr>
<tr>
<td>Ice Leg 5</td>
<td>153</td>
</tr>
<tr>
<td>Ice Leg 4</td>
<td>98</td>
</tr>
<tr>
<td>Ice Leg 3</td>
<td>107</td>
</tr>
<tr>
<td>Ice Leg 2</td>
<td>129</td>
</tr>
<tr>
<td>Ice Leg 1</td>
<td>120</td>
</tr>
<tr>
<td><strong>Total Distance for Ice Leg</strong></td>
<td><strong>1103</strong></td>
</tr>
<tr>
<td><strong>Distance to European Market (Bilbao)</strong> – Open water leg</td>
<td><strong>2100</strong></td>
</tr>
<tr>
<td><strong>Total Travel Distance</strong></td>
<td><strong>3203</strong></td>
</tr>
</tbody>
</table>

These assumptions will give the basis of the design for the simulation model and preliminary calculations made to verify required fleet sizes. The analysis on ice conditions and preliminary results on fleet requirements will be described in order to create the cases to be simulated in the later stage of evaluation.

These assumptions on the elements will be part of the modeling for the supply chain for LNG and further simulation in the tool used by Shell as well as other calculations made to analyze the example case.

5.2. Results for the selected supply chain concepts on the example case scenario

In this section, different results over the analysis for LNG Logistics under Arctic conditions will be shown. After understanding first what Arctic conditions are and how it can affect logistics and second describing the LNG supply chain, putting it down to an example case as the base for the research project and evaluate the performance on "real conditions". In the same way, the first step is to know what the impact of Arctic conditions is and therefore sea ice for this case. Then grasping the situation over requirements on fleet and capacity due to those conditions, to finally implement in the simulation and analyze the results. The objective at the end of this section is to verify how the supply chain for LNG can be composed and be financially interesting for the example case.

5.2.1. Sea ice conditions analysis for selected route

Sea ice is the impact implemented in the simulation of the LNG supply chain. As seen in Figure 5.2 there are two possible routes to follow to the European Market of LNG (the example used is Bilbao, Spain). A first comparison of the general conditions of distance and ice for both route determined that even through the Kara Gate route (#1) was
shorter, the sea ice was exposing the worst conditions and therefore the voyage duration would be longer and easy shipping would be less than the longer voyage over the north of Novaya Zemlya. For this reason the route north of Novaya Zemlya (#2) is the chose one to be used in the simulations and calculations for this research project. The process of analyzing the data of ice and how it is implemented as an impact on the voyage duration for the simulation will be described in this chapter.

### 5.2.1.1. Origin of Sea Ice data

The recollection of the sea ice data comes from a database called Canatech from the Metocean Engineering Department\(^7\). The data given to analyze the sea ice conditions is describing the distances of the different types of ice present along the route. Basic ice types were already described in Table 5.3 where it states the different thickness present in the ice and the speed assumed for the vessels. Depending on these factors, due to thickness for a relative distance, the voyage duration for the vessels will vary according to the speeds it can reach.

<table>
<thead>
<tr>
<th>Type of Ice</th>
<th>Distance [nm]</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice Free - Open Water</td>
<td></td>
<td>502</td>
<td>866</td>
<td>320</td>
<td>743</td>
<td>1,103</td>
</tr>
<tr>
<td>Nilas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gray</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gray White</td>
<td></td>
<td>87</td>
<td></td>
<td>176</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thin First Year (FY)</td>
<td></td>
<td></td>
<td>79</td>
<td>438</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium First Year (FY)</td>
<td></td>
<td>401</td>
<td></td>
<td>157</td>
<td>253</td>
<td></td>
</tr>
<tr>
<td>Thick First Year (FY)</td>
<td></td>
<td></td>
<td>112</td>
<td></td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>Old or Second Year (SY)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>58</td>
</tr>
<tr>
<td>Multi Year (MY)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unknown Type</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast ice</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Distance for Ice Leg [nm]</td>
<td></td>
<td>1,103</td>
<td>1,103</td>
<td>1,103</td>
<td>1,103</td>
<td>1,103</td>
</tr>
</tbody>
</table>

| Calculated Voyage Duration over Ice [hr] | 101 | 79 | 83 | 130 | 58 |

From the example of the data, the distance of certain types of ice can be found along each leg for different weeks. In Table 5.5 shows the data set for 5 random weeks can be

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\(^7\) Metocean, a word constructed from the contraction of the two words meteorological and oceanographic, is all about the weather and the oceans. Metocean Engineering is about describing the Metocean conditions prevailing in an area, deriving design criteria and providing operational statistics.
observed. From this point of information, and considering the assumed speed expressed earlier in Table 5.3 an average Voyage Duration can be established. A different way to see graphically is shown in Figure 5.4 where the example of Heavy Ice Scenario (PIO) is being used. In Figure 5.4 the different ice types and the distance they cover along the route per week can be observed. With the characteristics speed of the vessel, the approximate voyage duration can be calculated as will be described further on. The example shown in Figure 5.4 gives a good view of how the ice behaves along the year. In this figure the season can be observed for example as the summer has the ice melting down, on the contrary when the winter begins ice formation and thickening increases. Naturally during the other season, ice growth begins as the temperatures drop and sunlight diminishes. Therefore the different types of ice appear and then increasing the navigation difficulty which translates into a longer voyage duration. More details on voyage duration calculation will be given in the section below.

![Heavy Ice scenario (PIO)](Image)

Different sets of data were collected. Metocean delivered first the raw data from the database; this consists of 30 years of weekly sea ice information on the selected route. Not all weeks are available as will be shown later on. The second set of information is called PIO (heavy ice), P50 (average ice), and P90 (mild ice), defined also as percentiles from the data of the sea ice. Each of these scenarios represents the tenth percentage of worst ice cases from the full range of the database for a characteristic year. In this case, PIO will be the worst ice case, P50 is an average ice case and P90 is the mildest ice case. The data plot of the calculated voyage duration per week on a yearly base taken from the 30 years of available information on sea ice can be seen in Figure 5.5.
In Figure 5.5 the seasonality of the ice and how it affects voyage duration for the 30 years historic ice database is presented. In this case, end of the winter and beginning of the spring being the peak points and the lowest points are when the sea ice over the selected route is completely melted. The lowest points are when open water (no sea ice) occurs and therefore the maximum travelling speed is achieved for a minimum voyage duration.

5.2.2. Implementation of sea ice impact for simulation

As seen in Figure 5.5 the voyage duration can be translated into a variable affecting speed. Using this is how it will be implemented into the simulation in order to slow down or speed up the vessels according to the seasons of the sea ice. The minimum voyage duration is when there is no ice and the vessel can sail at maximum speed (in this example case is assumed to be 19 knots). Then anything above that will be a reduced percentage of the speed of the vessels and therefore reproducing the impact of the sea ice for the voyage duration along the route. This method is implemented for every week of the year per leg for the cases of the 30 year, the P10 (heavy ice), P50 (average ice) and P90 (mild ice). These ice cases will be the base for the rest of the calculations and simulations on the different supply chain concepts.
In Figure 5.6 the three cases of P10- Heavy, P50- Average and P90- Mild sea ice conditions for a characteristic year can be observed. Already by having the Voyage Duration, some calculations on fleet requirements can be made on a weekly base, thus some preliminary calculation can be done for the cases of Heavy, Average and Mild sea ice.

### Advantages of using SALSA

SALSA uses a Flexsim platform, which allows creating stochastic or deterministic events to affect the supply chain process. It was thought that with the historic data a probability distribution function could be obtained to simulate sea ice conditions with a stochastic behavior. In reality, the information turned out to be inadequate to be able to create models that reproduced the sea ice seasonal behavior as seen in Figure 5.5 or Figure 5.6. After analysis done over the behavior over the time due to the types of ice against probability distribution models, the behavior was not reproducible to create the same effect. Also the creation of a stochastic model would not have a continuous seasonality effect and therefore the behavior on the vessels navigation would not be close to a real situation. For these reasons the decision is made then to support the utilization of the three basic sea ice scenarios (P10- Heavy, P50- Average, P90- Mild) as they are representing the basic range of the information and it was proven from the historic data to corroborate this fact as can be seen in Table 5.6.

The intention with Table 5.6 is to show how by using the ice scenarios given by the database (P10- Heavy, P50- Average and P90- Mild) are inclusive compared to the raw data and the percentiles obtained from it. Here the percentiles of the weekly information for 30 years are showed and put against the ones given for the P Scenarios. Comparing for example the Percentile 90 against the correspondent P10, it can be determined that P10 or the heavy ice scenario is having extreme voyage duration. The conclusion to finally use the P Scenarios as the base case for first design stage is taken as the values represent the information from the raw data. This was done as a confirmation to the decision taken before as the probability distribution of the ice was not able to reproduce.
Furthermore, simulations using a time period of 30 years is very time consuming and not practical in this stage of the research. With confidence the utilization of the P Scenarios will give sufficient base to obtain results for the simulation cases that will be run later on to create the time series which will affect the behavior of the voyage duration for the LNG supply chain.

By means of the P scenarios the time series for a characteristic year is then implemented to be used in the three cases of sea ice (heavy, average, and mild). This will allow verifying the behavior of the supply chain in variable conditions of sea ice and the results of the performance for the supply chain designs can be compared in heavy, average or mild ice for longer periods of time.

For a later stage in the simulation, the 30 year historic data will be used to confirm the performance of the supply chain concepts under variable conditions for a long period and therefore the behavior under a more variable ice case. This is not possible to implement for all cases as it very time consuming and can’t be delivered within the time scope of the project.
Table 5.6: Comparison of average voyage duration (hr) between percentiles from historic data against database scenarios

<table>
<thead>
<tr>
<th>Week</th>
<th>RAW DATA - PERCENTILES</th>
<th>P SCENARIOS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.90</td>
<td>0.50</td>
</tr>
<tr>
<td>1</td>
<td>115.31</td>
<td>97.75</td>
</tr>
<tr>
<td>2</td>
<td>124.78</td>
<td>99.60</td>
</tr>
<tr>
<td>3</td>
<td>121.29</td>
<td>100.36</td>
</tr>
<tr>
<td>4</td>
<td>120.29</td>
<td>104.20</td>
</tr>
<tr>
<td>5</td>
<td>138.54</td>
<td>106.98</td>
</tr>
<tr>
<td>6</td>
<td>133.36</td>
<td>102.77</td>
</tr>
<tr>
<td>7</td>
<td>130.69</td>
<td>111.69</td>
</tr>
<tr>
<td>8</td>
<td>132.32</td>
<td>111.69</td>
</tr>
<tr>
<td>9</td>
<td>132.92</td>
<td>120.62</td>
</tr>
<tr>
<td>10</td>
<td>128.40</td>
<td>110.87</td>
</tr>
<tr>
<td>11</td>
<td>137.23</td>
<td>117.91</td>
</tr>
<tr>
<td>12</td>
<td>139.60</td>
<td>110.54</td>
</tr>
<tr>
<td>13</td>
<td>138.00</td>
<td>118.63</td>
</tr>
<tr>
<td>14</td>
<td>141.32</td>
<td>113.66</td>
</tr>
<tr>
<td>15</td>
<td>143.22</td>
<td>122.04</td>
</tr>
<tr>
<td>16</td>
<td>125.16</td>
<td>118.35</td>
</tr>
<tr>
<td>17</td>
<td>142.87</td>
<td>122.07</td>
</tr>
<tr>
<td>18</td>
<td>139.09</td>
<td>115.06</td>
</tr>
<tr>
<td>19</td>
<td>146.45</td>
<td>125.03</td>
</tr>
<tr>
<td>20</td>
<td>142.50</td>
<td>118.89</td>
</tr>
<tr>
<td>21</td>
<td>142.61</td>
<td>121.38</td>
</tr>
<tr>
<td>22</td>
<td>140.63</td>
<td>121.43</td>
</tr>
<tr>
<td>23</td>
<td>144.15</td>
<td>122.66</td>
</tr>
<tr>
<td>24</td>
<td>133.70</td>
<td>117.78</td>
</tr>
<tr>
<td>25</td>
<td>143.34</td>
<td>112.97</td>
</tr>
<tr>
<td>26</td>
<td>131.68</td>
<td>102.69</td>
</tr>
<tr>
<td>27</td>
<td>130.42</td>
<td>102.14</td>
</tr>
<tr>
<td>28</td>
<td>116.27</td>
<td>96.95</td>
</tr>
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<td>29</td>
<td>109.53</td>
<td>90.03</td>
</tr>
<tr>
<td>30</td>
<td>100.51</td>
<td>84.78</td>
</tr>
<tr>
<td>31</td>
<td>103.95</td>
<td>77.13</td>
</tr>
<tr>
<td>32</td>
<td>93.31</td>
<td>70.65</td>
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<tr>
<td>33</td>
<td>88.76</td>
<td>70.02</td>
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<tr>
<td>34</td>
<td>73.95</td>
<td>63.41</td>
</tr>
<tr>
<td>35</td>
<td>72.02</td>
<td>60.25</td>
</tr>
<tr>
<td>36</td>
<td>68.18</td>
<td>58.10</td>
</tr>
<tr>
<td>37</td>
<td>64.98</td>
<td>58.10</td>
</tr>
<tr>
<td>38</td>
<td>64.54</td>
<td>58.10</td>
</tr>
<tr>
<td>39</td>
<td>67.57</td>
<td>58.10</td>
</tr>
<tr>
<td>40</td>
<td>87.07</td>
<td>58.10</td>
</tr>
<tr>
<td>41</td>
<td>77.37</td>
<td>59.79</td>
</tr>
<tr>
<td>42</td>
<td>94.65</td>
<td>69.96</td>
</tr>
<tr>
<td>43</td>
<td>97.34</td>
<td>76.99</td>
</tr>
<tr>
<td>44</td>
<td>102.19</td>
<td>84.19</td>
</tr>
<tr>
<td>45</td>
<td>119.45</td>
<td>84.78</td>
</tr>
<tr>
<td>46</td>
<td>113.04</td>
<td>84.78</td>
</tr>
<tr>
<td>47</td>
<td>126.03</td>
<td>83.93</td>
</tr>
<tr>
<td>48</td>
<td>111.58</td>
<td>84.78</td>
</tr>
<tr>
<td>49</td>
<td>114.50</td>
<td>87.10</td>
</tr>
<tr>
<td>50</td>
<td>119.94</td>
<td>88.56</td>
</tr>
<tr>
<td>51</td>
<td>109.71</td>
<td>93.00</td>
</tr>
<tr>
<td>52</td>
<td>114.74</td>
<td>98.23</td>
</tr>
</tbody>
</table>

Average: 116.56 | 95.18 | 78.86 | 135.69 | 99.07 | 71.55

5.2.3. Preliminary calculations
For a quick reference tool to create the scenarios to be simulated in SALSA, a calculation sheet with the impact of sea ice on the route was developed. With this tool, preliminary
calculation on fleet size requirements according to cargo capacity of the vessels is obtained. On weekly basis, considering the objective of transporting the full level of production assumed for the base case, the requirement calculates the amount of vessels with a certain cargo capacity needed to transport the full production according to the voyage duration and operation times in the ports. This is an indication of the minimum and maximum fleet size required according to the season of the sea ice. From this point a range of fleet sizes can be defined to later implement in the simulation cases.

The calculation is done considering the following assumptions:

- Port Operation time: 30 hours at Arctic production locations and 24 hours at delivery port
- Use of weekly sea ice impact according to the P Scenarios (P10- Heavy, P50- Average and P90- Mild).
- Assigned LNG production (for these results a 16 mtpa production was used)

In order to find out the fleet size for every week, the formula used was:

\[
\text{Weekly required fleet size} = \frac{\text{Total Production}}{\text{Period of Time}} \times \frac{\text{Total Voyage Duration}}{\text{Cargo Capacity}}
\]

In this example case, the weekly required fleet was calculated based for the yearly production. What this means is that assuming that each week, the voyage duration would be the same for the whole year, the number of LNG carriers would correspond. For this reason the formula described above corresponds to the following definitions:

- Total Production: Yearly production, which for the example is set to 16 mtpa
- Period of Time: As explained before, assuming the weekly information would be the same for a whole year, the used period for this calculation was a year.
- Total Voyage Duration: The time it takes a vessel to load, transport, deliver and return to port, in this case according the weekly sea ice conditions.
- Cargo Capacity: Characteristic of the LNG Carrier, which can be modified for different capacities. For the results presented here a cargo capacity of 100,000 m³ for the LNG carriers (both ice capable and open water) was used.

For example the results for the case of an Arctic Conventional Supply Chain Concept (from production to the market) can be seen in Figure 5.7 after using the formula explained before. The fleet size required for LNG Ice Carriers, according to a weekly impact of sea ice in order to be able to deliver a full production for a year is changing according to the season of the ice. The calculations shown here were made for a 100,000 m³ cargo capacity per vessel. The tool allows changing this cargo capacity and delivering the results for different cargo capacities.
Figure 5.7: LNG Ice carriers' fleet size required for a conventional concept, on a weekly base to deliver full production according to different ice scenarios

When considering the case of a Transshipment Concept for the LNG supply chain, a similar calculation is obtained as Figure 5.8 illustrates. For this case an additional time was established to deliver the cargo at the transshipment point. In order to recreate the transshipment situation (as for the supply chain design of Hub to Ship and Ship to Ship) an additional time was implemented into the total voyage duration; therefore adding time now to both fleets separately. The times are added for the ice fleet and also for the open water one like this: first additional time to unload from the LNG Ice Carrier and then to load into the LNG Open Water Carrier. In theory, right after the unloading and loading procedure is completed the LNG can continue its journey up to the demand market.

Figure 5.8: LNG Ice carriers' fleet size required for a transshipment concept, on a weekly base to deliver full production according to different ice scenarios
In the Transshipment Case, the number of vessels required will be divided in two fleets for both the ice area and the open water area. As separate fleets, each one will have less distance to travel and the voyage duration for each fleet is reduced, except the total voyage time for the product (for this example LNG). That's the main reason to observe a reduction in the required fleet size for the LNG Ice carriers. For this case the mentioned vessels, only have to travel to an intermediate point to deliver their cargo and return to the production port. After or during delivery, the open water fleet is ready to receive and transport the LNG to the demand market (Bilbao for this example). So even though in the figure a lower requirement for the LNG ice carriers is found, the dotted yellow line shows the required number of vessels for the open water section of the voyage after the transfer of LNG is done. Of course, the Ice fleet is changing according to the ice scenario and the season. But the open water fleet is not being disturbed by any event in this example, so only voyage duration and total production to be delivered is being considered.

Observations on the preliminary calculations
The quick calculation tool is proven to be a good reference point. Already some observations can be made from these results, which will help in the development of the simulation scenarios.

The most relevant points of the calculations are:

- The selection for an ice base case can already determine a certain risk level to either loss production or underutilize resources. If a fleet selection would be based on a P90 – Mild Ice scenario, it can already be determined that there is a wide range of fleet required (approximately 18 vessels during winter and 16 during the summer) which can translate into losing production. But in the opposite case, if the maximum fleet size would be based on a PIO – Heavy ice is selected (approximately 27 vessels during the winter and 16 during the summer), then there are also periods which the overall utilization of the fleet will be low and can risk an unnecessary investment.
- The window for open water is reduced as the conditions of ice worsen. During the summer period, the minimum fleet gives an indication of ships that could go into maintenance as there will always be some vessels in idle state, as the voyage duration is shorter.
- Using the Voyage duration for all ice scenarios, against the production seasonality for LNG, it shows that their peaks are shifted from each other in approximately 3 months. This can give an advantage in the definition of fleet size requirements, as for a monthly production level during the worst voyage duration cases, most likely the fleet size is lower in combination with both factors. Figure 5.9 shows both production peaks and voyage duration.
The preliminary calculations give a range of parameters which can be further analyzed with the simulation. With these preliminary results the shipping of LNG is easily understood, but there are other elements to be considered in the supply chain, therefore the need to implement a simulation and analyze its results.

### 5.2.4. Simulation results

Using the simulation tool, gives the advantage to have an overall results of combination for different elements and their characteristics in the LNG Supply Chain. The results presented here allow the reader to have a perspective of what was obtained from the simulations and the scenarios created from the concepts presented in Section 4.2. Not all the results of all the simulation cases are presented here. An overview of which results are obtained from the simulations and how they could be compared is described. At the end all the results are assessed to make a selection of the best performing supply chain concepts according to the key performance indicators.

### Scenarios for the simulations

The selection of the characteristics of the different elements was done thought the advice of people with experience in the design of facilities to produce LNG. The calculation tool developed in the Section 5.2.3 will help in the selection of the fleet size according to the recommended vessels capacities.

Table 5.7, presents the list of the characteristics of the elements used to run the simulations. A combination per Supply Chain Concept was created. These characteristics were taken from alternatives considered for similar projects.

<table>
<thead>
<tr>
<th>Production Storage Tank Capacity:</th>
<th>Arctic Conventional</th>
<th>Hub to Ship</th>
<th>Ship to Ship</th>
</tr>
</thead>
<tbody>
<tr>
<td>280.000 m³</td>
<td>350.000 m³</td>
<td>280.000 m³</td>
<td>280.000 m³</td>
</tr>
<tr>
<td>480.000 m³</td>
<td></td>
<td>480.000 m³</td>
<td>350.000 m³</td>
</tr>
</tbody>
</table>

LNG logistics under Arctic conditions

C. Higuera
<table>
<thead>
<tr>
<th>Arctic Conventional</th>
<th>Hub to Ship</th>
<th>Ship to Ship</th>
</tr>
</thead>
<tbody>
<tr>
<td>480.000 m$^3$</td>
<td>-</td>
<td>480.000 m$^3$</td>
</tr>
<tr>
<td>640.000 m$^3$</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

| Hub Storage Tank Capacity: | - | 160.000 m$^3$ | - |
|                          |   | 240.000 m$^3$ |   |

| Vessel Cargo Capacity: | 50.000 m$^3$ | - | - |
|                       | 75.000 m$^3$ | 75.000 m$^3$ | 75.000 m$^3$ |
|                       | 100.000 m$^3$ | 100.000 m$^3$ | 100.000 m$^3$ |
|                       | 150.000 m$^3$ | 150.000 m$^3$ | 150.000 m$^3$ |

<table>
<thead>
<tr>
<th>Fleet Size for LNG Ice Carriers:</th>
<th>Range from 5 to 50 vessels</th>
<th>Range from 7 to 24 vessels</th>
<th>Range from 7 to 24 vessels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-</td>
<td>15 for 75.000 m$^3$</td>
<td>15 for 75.000 m$^3$</td>
</tr>
<tr>
<td></td>
<td>11 for 100.000 m$^3$</td>
<td>11 for 100.000 m$^3$</td>
<td>11 for 100.000 m$^3$</td>
</tr>
<tr>
<td></td>
<td>8 for 150.000 m$^3$</td>
<td>8 for 150.000 m$^3$</td>
<td>8 for 150.000 m$^3$</td>
</tr>
</tbody>
</table>

Following the objective to find a robust concept for Arctic that can mitigate the impact of sea ice, alternatives with different capacities are evaluated. All these runs were done using SALSA as the simulation tool for the concepts of supply chain. Implementing the sea ice impact for PIO- Heavy, P50- Average and P90- Mild for a characteristic year. Each scenario was first run for one “star up” year and only the second year results were considered once the process is stable.

A line up of the results to understand the outcomes of SALSA is presented in the following analysis.

5.2.5. Output from SALSA simulations

As described in Section 4.4.2, there are different key performance indicators to focus according to Shell’s experience. An overview of these results will be given for certain interesting cases and observations will be made at the end.

Analysis of key performance indicators from examples

The objective of an LNG plant is to deliver as much product as possible. The investment made on this facilities need to be recovered and make a business out of it. Different indicators can measure the production for an LNG Plant. The first one of course is the level of production reached compared against the designed production for the plant. The second one is the production loss and the number and duration of tank tops directly relate this one to the simulation case of this project.
Figure 5.10 gives an example where the production level is never met. For the case simulated on a Conventional Arctic concept including a Storage Tank of 280,000 m$^3$ and LNG Ice Carriers with cargo capacity of 50,000 m$^3$ for different fleet size. In both extreme cases of PIO- Heavy and even P90- Mild sea ice scenario, the combination cannot be able to deliver the performance to produce the total of LNG the plant is designed to do.

Also the number of Tank Tops is a number to consider. For Tank Tops not only the frequency but the duration is an issue to consider for losses in production. For example, referring to the P90 graph, for a 5 vessels fleet, the number is lower, but still the production lost is approximately 85%. Contrary for the case of 20 vessels, where the number of Tank Tops almost triple, but still the production level is approximately doubled.

Here the duration of the tank tops becomes an issue. In Figure 5.11 already P90- Mild ice shows more frequencies but with less duration compared to PIO- Heavy Ice, where the longer durations become more frequent. By averages in duration the estimation can be made that P90's are shorter with an average of 5.3 hours and a maximum case of 59.6 hours duration Tank Top. On the case of P10, the average goes up to 8.9 hours and a maximum case of 64.7 hours. A direct way to view this on a daily base is on the tank level. An example of how to analysis this can be seen from Figure 5.12. Here the frequency and the duration are represented by each time the blue line hits the maximum capacity. Once the line reached the maximum capacity a Tank Top is declared. It will continue in this state as long as the line stays over this maximum and the duration can be translated into hours or even days. In order to obtain the details, digging into the numbers is required, but already this figure gives a good first look at this tank top behavior.
Finally the production level also reaches a maximum level after 30 ships. When the production stabilizes and even increasing the fleet size, no further production can be obtained, it only means that the shipping cargo reached its limit and other element has become the restricting factor for the supply chain performance. In this case, looking for example at a bigger Storage Tank as shown in Figure 5.13 the production stay “stuck” at the same level. Thus other elements can be looked into like for example loading capacity.
The last element to look at is the Port with the loading arms. In the base case used for the simulation, there is a limit of only two berths available for loading of LNG. Indeed when looking at Figure 5.14, the utilization of the berths after 30 ships of fleet size has reached its full operation capacity. To achieve sufficient flexibility for the time windows of ship arrival and activities the utilization level should be approximately 70%. The recommended level for this element according to the expert shouldn't reach approximately above 70%. In this case, Berth 1 has reached 100% and Berth 2 is also close to the same utilization level. In this case, the limiting factor therefore is the loading capacity as for example with an additional berth and its installations. If a new case could be run with more capacity, most likely better production levels could be reached.
Looking for a better performing supply chain in the Arctic Conventional concept, the example of 100.000m³ Cargo Capacity Ships is described. As shown in Figure 5.15 the production level is reached for both ice cases (P90- Mild and P10-Heavy) at least for 25 ships. In this supply chain combination and for the example case this project is working on shows that when no tank tops are reached, the full production can be achieved.

For the ice scenario of P10- Heavy, when 22 ships are used, production is reached approximately on 95%. On the other side, for P90- Mild ice conditions, the level of production is reached completely. This might indicate that when the ice conditions are not heavy, this combination might be able to reach the full production expected for the season (according to LNG Production Seasonality). To verify this, it is necessary to look...
into the tank level graph. In Figure 5.16 the Tank Level reaches Tank Tops during the months where travel time is highly affected by the sea ice (in this case winter, spring principally). During the summer and autumn, the shipping capacity is sufficient to deliver the full production of the LNG Plant, and can even get some low utilization values for the fleet and the storage tanks.

In the case of low utilization of the Storage Tank capacity, an assessment of the distribution of the level of the tank can be made. The objective of this assessment is to verify the frequency a certain level is reached and therefore a better estimation on the right Storage Tank required capacity could be made. An example of how can this be seen is given in Figure 5.17. Here the frequencies of certain levels of Storage in the tank are shown. Finally the overview of the general Tank level as given in Figure 5.16 allows a better planning in the production as it indicates the seasons when more tanks tops could occur. Preparedness for this sort of situations can make the difference into reaching a Tank Top or not, by means of slowing down the production (some lost production) or trying to speed up the next coming LNG Ice Carrier (avoid any production loss).

![Tank Level Graph]

Figure 5.16: Daily Tank Level for conventional supply chain under P10-Heavy Ice, with 280,000 m³ Storage Tank, 100,000 m³ Cargo Vessel and 22 ship fleet
The tank level as seen before can help identify the production lost due to the tank tops. In this case the idea of increasing the tank size could be an alternative to have a more flexible buffer for the production to continue. Even though increasing storage capacity is without a doubt the first alternative, further research perhaps shows the answer lays over a cheaper or easier choice. Still in experience and costs, increasing tank capacity is sometimes the preferred way to go. In Figure 5.17 approximately 40% of the time the tank level is above 200,000 m$^3$. Being at this level is considered high and therefore tank tops occur easily. To contrast this situation the P90- Mild ice scenario is also observed.
As seen in Figure 5.18 the tank storage level stays very low, not even reaching the 100,000 m$^3$ level. With this contrast the focus goes to the impact of the ice scenario which affects the voyage duration. With a PIO-Heavy ice scenario the LNG Ice Carriers are staying behind in the arrival frequency, against the easier voyage that takes place on the P90-mild ice scenario. Therefore the capacity restriction in for the PIO is the shipping size with a limited fleet size for the voyage duration it takes to deliver the LNG to the demand market. As the voyage duration is reduced, the fleet requirement in the P90 ice scenario is reduced in the same way.

For the case of the Conventional Supply Chain design with a 100,000 m$^3$ cargo capacity vessel, Figure 5.20 shows how in the same way as the size of fleets allow more vessels to be available, then the occupancy at the berths increases. This is also related to the voyage duration due to the ice severity for the example ice scenarios shown (P90-Mild and PIO-Heavy). For the example case used for this research project, the highest occupancy is preferred. Similar as in Figure 5.15 for P90 at 20 ships there is no production loss and with an ice scenario of PIO the requirement is close to 25 vessels. Utilization can never reach the full 100% as there are other operations taking place on the berth accounting for operation of arrival and departure. This indicator is only to show when there are ships ready to load.
Another way to assess the production reached is by the monthly rates. In average this indication points out if in general terms the supply chain is performing to reach the maximum production or in which cases it might not. In Figure 5.21 the monthly production for all ice cases does not change between a small or a larger Storage Tank Capacity. Of course for P90-Mild Ice, the production is reached completely. On the contrary, only over a couple of months for P50- Average Ice the production is reached completely during the summer seasons and P10- Heavy Ice, goes even lower for the seasons different than the summer. In this cases, the impact of having a much larger capacity for Storage Tank shows that the improvement of production can only be of 0.54% when P50- Average Ice conditions are considered. In the case for P10- Heavy ice, the improvement is slightly better as with a bigger tank production increases in a 0.64%, still not sufficient to support the decision to build such capacity. This could indicate that the storage tank is apparently not the limiting factor in this case.

A difference could be made, if in this case the limiting element increases its capacity. For example when the fleet size is increased to 30 vessels instead of 25 as shown before. From Figure 5.22 already the improvement is seen as for the P50- Average Ice Conditions, the monthly production rate can be fully completed. This verifies that the limiting factor in this case is the shipping capacity (as was already determined form the
examples from Figure 5.21). This can be determined that while the production loss is reduced or the production reached increases, adding shipping capacity improves the performance. Until the effect is gone and no further production can be reached and then, the following limitation should be found. On the other hand, again for the particular case of using 30 ships, the increased Storage Capacity is not helping to improve the production level but only on a 0.47%.

![Storage Tank 280,000 m³](image1)

![Storage Tank 480,000 m³](image2)

Figure 5.22: Monthly production levels for a Conventional supply chain with 75,000 m³ cargo capacity vessel and 30 ship fleet

An additional way to compare supply chain performances is on number of deliveries when using the same vessel cargo capacity. In this example, comparing the Transshipment supply chain concepts will be used. In the case shown in Figure 5.23, using the Hub to Ship concept more deliveries are being made. This comparison is giving specific information to compare supply chain performances, but detailed information on the individual performance of the supply chain should always be looked at. For example arrival times are crucial in a transshipment concept as the Ship to Ship. The importance of this is because one fleet will become dependent from the other one (in this case the LNG Ice Class fleet and the LNG Open Water fleet). Depending on the season of ice more or less vessels will be required, but if too low shipping capacity is present on one side, there will always be a limitation. Also from the examples described before, if the shipping capacity is increased, then the loading berths could become also a bottleneck.
5.2.5.1. Observations made from the results obtained from the simulation

After the simulations were done and the complete analysis of the data was finished, some interesting observations for the example cases were made:

- 50,000 m³ cargo capacity vessels become a fleet that's too large and therefore difficult to handle for the port. Unless increasing capacity in the loading berths is implemented, this type of vessels shouldn't be considered.

- Increasing the Storage Tanks capacity doesn't give such an advantage when there is enough capacity in the shipping side (fleet size and cargo volume). On the other hand, when a small fleet is being used which can't deliver the whole LNG production, then increasing Storage Tank capacity becomes more interesting as it allows production to continue resulting in fewer losses. Nevertheless the difference between increasing Storage Tank capacities only reaches a considerable low benefit.

- Due to the assumptions used in this example case the shipping capacity is the main limiting factor for this simulation case as it is the one being affected by the sea ice. But it serves the purpose of the research study to understand the impact of the main disturbance (sea ice) for an Arctic area.

- The loading capacity can only handle a certain number of vessels. The frequency of loading is a quick reference to determine how busy the port could be. This helps in pointing out when the increasing of the fleet size doesn't help in increasing the production of LNG if there is still a limiting in the number of loading berths for example.

- The difference in the ice scenarios used is already giving the insight of the risk that would be taken if for example a mild case is chosen against a heavy case. It is easily recognizable how when a supply chain is successful in delivering good performance indicators in a P10- Heavy Ice scenario, in the P50- Average and P90- Mild, the same indicators are easily reached and even spare capacity is available. The other way around is also identified, that being successful in a P90-Mild ice scenario, doesn't necessarily mean that in a P10-Heavy the supply chain will be
able to deliver. This indicates how could it behave in a stochastic scenario, but tests should be done to verify how steady the performance indicators really are.

- The Hub to Ship concept performs better than the Ship to Ship. The flexibility the Hub Storage Tank give to the supply chain can’t be compared to the waiting times, the Ship to Ship concept is forced into. The Ship to Ship concept is limited either by the Ice Fleet or the Open Water Fleet. In the case of limitation by the Ice Fleet, it is delayed by the sea ice impact; therefore the Open Water Fleet has to wait. On a different alternative, if the Open Water is increased, there are still waiting times, as the Loading capacity can’t handle the large quantities of vessels.

- As in any supply chain enough capacity of it elements and their interaction between them and the environment will determine the best production level (for the example case against the difficulties given by the sea ice). For the example case used and the simulations made for this section, already the preference for a robust supply chain is going towards the conventional concept. Of course in the conventional concept any simulation runs were made and not all were successful to deliver the production over the different ice scenarios (for example using the 50,000m³ cargo capacity vessels). The results of not fulfilling the maximum LNG production should be analyzed with further combinations for simulation, but for this research project the time limitation doesn’t allow to continue investigating more alternatives. The Hub to Ship concept also gives a certain advantage to deliver production, but once again due to time limitation not more simulations can be run to gain knowledge over the possibilities for this concept. The Ship to Ship concept showed a very limited performance and could be an alternative that could be discarded.

- Finally not always increasing capacity is better and as was shown the elements aren’t fully independent from each other. Therefore increasing capacity on one side could mean getting short on the other. However once this relation is understood and fully analyzed a size selection can be made. It will be found that different combination can deliver a good performance and robustness for the LNG supply chain under Arctic conditions, therefore an economic analysis has to be done to balance both worlds of operations and finances.

5.2.6. Economic Evaluation based on simulation results

The operational performance indicators have given a perspective on what each supply chain can deliver. The balance in obtaining the maximum production against the highest return keeps the motion of the LNG business. In this case, as the simulations are delivering the total LNG that’s being produced, the revenues expected from each supply chain can be estimated. In this section the differentiation between supply chains will be done by using the performance outcome by the production of LNG against assumed costs for the project. This will determine the final balance of which supply chain is better performing from the two points of view for the business.

Assumed costs for the elements of the supply chain

The values described in this section are approximations from data experts within Shell that have experience from other projects. They are used as a reference and with the main purpose of being able to differentiate economic performance of the supply chain for this research project.
On the revenues side, an estimated price for LNG is defined as 209 US$/m$^3$ (Indexmundi, 2011). This rate will be used to calculate the revenues of the supply chain from the total production it is delivering to the market.

For the supply chain, the investment costs to have the different elements in place are mostly the approximations used per unit of LNG it contains. For most of the elements included in the LNG Supply Chain, an operational cost, maintenance, etcetera, will also be considered as a percentage from the initial investment cost. As see in Table 5.8 all costs per unit of LNG are listed. From this unit cost, the cash flow will be made for an approximate time of 30 years, which is the life time of a project for LNG production.

<table>
<thead>
<tr>
<th>Supply Chain Element</th>
<th>Investment - Capex</th>
<th>Opex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Storage Tank [$/m$^3$]</td>
<td>$1,875</td>
<td>$94</td>
</tr>
<tr>
<td>Ice Carrier [$/m$^3$]</td>
<td>$2,333</td>
<td>$586</td>
</tr>
<tr>
<td>Open Water Carrier [$/m$^3$]</td>
<td>$1,333</td>
<td>$502</td>
</tr>
<tr>
<td>Transshipment Facilities (Port: 1 Jetty, 2 Berths)</td>
<td>$150,000,000</td>
<td>$4,500,000</td>
</tr>
<tr>
<td>Hub Storage Tank [$/m$^3$]</td>
<td>$1,250</td>
<td>$63</td>
</tr>
</tbody>
</table>

Finally the cost of obtaining the LNG will be assumed to be at a 30% margin profit from the LNG revenue price and the discount rate for the project will be set to be 10%.

Using these values, the cash flow for all the supply chains simulated in SALSA was calculated. For example, for the case presented in Figure 5.25, the NVP (Net Present Value) obtained is -$3,140,376,994 and -4.75% IRR (Internal Return Rate). These values make it unattractive supply chain, even though it is able to deliver the full production in a P10- Heavy ice scenario.
In Figure 5.26, having a 280,000 m$^3$ Storage Tank, 75,000 m$^3$ Cargo vessel, 22 ship fleet the NPV obtain is $6,880,110,631 and an IRR of 15.19%. As both indicators are positive, the operational side is only delivering 96.4% of the production. Even the economics are delivering a positive outcome, and with the expected production there is still economic benefit, the ice base design is for a P90- Mild. That implies a risk of not being able to deliver even further amounts of LNG and making the project less attractive. However it should be a case to consider for further evaluation.

Finally a case where full production is delivered with positive financial indicators for a P50-Average Ice scenario is shown in Figure 5.27. In this case, operationally and financially the project is delivering positive numbers as it is able to produce the full designed capacity of the LNG Plant and financially the NPV is $3,340,352,675 and the IRR 5.9%. The payout time of 10 years is also used as an indication of acceptable business, but it is still very long. However these financial indicators are used mainly as a reference to differentiate projects between each other.
Figure 5.27: Cash flow for Conventional Supply Chain under P50- Average ice with 280.000 m³ Storage Tank, 75.000 m³ Cargo vessel, 22 ship fleet

There are other supply chains that perform similarly and are summarized in Table 5.9.

Table 5.9: List of best performing concepts for example case simulations

<table>
<thead>
<tr>
<th>Supply Chain Concept</th>
<th>Ice Scenario</th>
<th>Production Storage Tank Capacity</th>
<th>Hub Storage Tank Capacity</th>
<th>Vessel Capacity</th>
<th>Total Fleet</th>
<th>Ice Fleet</th>
<th>Open Water Fleet</th>
<th>Production Completion</th>
<th>NPV</th>
<th>IRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional P10</td>
<td>280,000</td>
<td>-</td>
<td>100,000</td>
<td>25 25</td>
<td>-</td>
<td>100%</td>
<td>-</td>
<td>$ 828,259,728</td>
<td>$ 982,496,847</td>
<td>1.62%</td>
</tr>
<tr>
<td>Conventional P10</td>
<td>350,000</td>
<td>-</td>
<td>100,000</td>
<td>25 25</td>
<td>-</td>
<td>100%</td>
<td>-</td>
<td>$ 789,382,720</td>
<td>$ 789,382,720</td>
<td>1.28%</td>
</tr>
<tr>
<td>Conventional P10</td>
<td>480,000</td>
<td>-</td>
<td>100,000</td>
<td>25 25</td>
<td>-</td>
<td>100%</td>
<td>-</td>
<td>$ 430,742,200</td>
<td>$ 430,742,200</td>
<td>0.68%</td>
</tr>
<tr>
<td>Conventional P10</td>
<td>280,000</td>
<td>-</td>
<td>75,000</td>
<td>35 35</td>
<td>-</td>
<td>100%</td>
<td>-</td>
<td>$ 56,918</td>
<td>$ 56,918</td>
<td>0.00%</td>
</tr>
<tr>
<td>Conventional P50</td>
<td>280,000</td>
<td>-</td>
<td>100,000</td>
<td>22 22</td>
<td>-</td>
<td>100%</td>
<td>-</td>
<td>$ 3,340,352,675</td>
<td>$ 3,340,352,675</td>
<td>5.94%</td>
</tr>
<tr>
<td>Conventional P50</td>
<td>350,000</td>
<td>-</td>
<td>100,000</td>
<td>22 22</td>
<td>-</td>
<td>100%</td>
<td>-</td>
<td>$ 3,147,238,549</td>
<td>$ 3,147,238,549</td>
<td>5.49%</td>
</tr>
<tr>
<td>Conventional P50</td>
<td>280,000</td>
<td>-</td>
<td>75,000</td>
<td>30 30</td>
<td>-</td>
<td>100%</td>
<td>-</td>
<td>$ 2,947,376,704</td>
<td>$ 2,947,376,704</td>
<td>5.17%</td>
</tr>
<tr>
<td>Conventional P50</td>
<td>280,000</td>
<td>-</td>
<td>150,000</td>
<td>15 15</td>
<td>-</td>
<td>100%</td>
<td>-</td>
<td>$ 2,947,376,704</td>
<td>$ 2,947,376,704</td>
<td>5.17%</td>
</tr>
<tr>
<td>Conventional P50</td>
<td>350,000</td>
<td>-</td>
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The step here to consider is that since these results are taken from the characteristics years of the ice scenarios, is to evaluate the performance on a variable ice case. Once this evaluation is made, the robustness of the design can be assessed and better economic estimates can be done on a year operational revenues. The cases listed in Table 5.9 are the best performing (operational and financial) supply chain concept alternatives according to an specific ice scenario. All these cases will be simulated over a completely variable 30 years historic data to obtain further results in the following section.

5.2.7 Robustness test against the 30 years ice historic data

A selection of supply chains was made on the best performing cases run over the ice characteristics years (P10- Heavy, P50- Average and P90- Mild). These selected supply chains were run under the ice conditions of the 30 years historic data. These runs were
made in order to test how the combinations of the LNG supply chain elements are able to mitigate the consequences of the sea ice.

One example for each ice condition is shown to analyze the decrease on the performance against the characteristic years simulation done in the section before.

From Figure 5.28 the elements are delivering all the production the LNG Plant is designed for with a P10- Heavy ice scenario, also the financial indicators are positive. When implementing the long-term variable conditions of the historic data, it can be seen by the figure, that on a yearly base the production is completed except on the year 2042, which is also a very heavy ice scenario. For the 30 year simulation the completion of the production is in average 99.9%. Also the financial indicators are positive as well, considering the revenues from the LNG produced each year. The NPV is $940,421,090 and the IRR is 1.6%, the payout time is approximately 18 years. The payout time indicates the high investment and therefore the utilization of the element of the supply chain is low, making the design for a P10- Heavy ice redundant in its capacity.

![Figure 5.28: Conventional supply chain yearly production for 30 years under P10- Heavy ice conditions with 280.000 m³ Storage Tank, 100.000 m³ Cargo Capacity Ship, 25 ships fleet](image)

For the P50- Average ice scenario in Figure 5.29, the production reached on a 30 years simulation is able to complete 99.3% from the designed level. From the figure, only 3 years the production is not fulfilled but from Figure 5.5 it is seen as peak years from the historic data. An interesting point to consider is that even the production is lower than in the case described before, the financial indicators show a higher value as the NPV is $3,076,323,094 with an IRR of 5.5% and 11 years as payout time. The balance between the investment on the elements of the supply chain and the production is then found to have good outcome. The risk of designing over an ice scenario of P50- Average could be a good alternative to consider for future projects.
Finally, using a P90- Mild ice scenario the production reaches in average 90.9% in a variable ice as used for the 30 years simulation. In Figure 5.30 the yearly production is only met for one year, therefore the investment for the LNG Plant could be in risk with this performance from the supply chain. Also as the production is low, the returns on financial terms are lower compared to the P50- Average ice scenario. Even though the initial investment is lower, the NPV is equal to $2,958,026,132 with an IRR: 5.8% and payout time of 11 years. In financial terms it is close to the P50- Average ice design base, but as the production is often not met, P90- Mild ice is decided to not be a good design base.
This test has supported further how using a certain ice scenario for design base and later simulation to verify performance of the system will determine certain levels of utilization and production reach. This is important for a company trying to decide over which scenario to use, for example to have an idea of how a system will behave considering a P10- Heavy ice case, it can be said that the supply chain will have spare capacity which in a business case can define if the investment will be made or not. In the same way if using a P90- Mild ice scenario as the design base to test it against a real situation, the production lost will translate into lost sales, which will make a business case less interesting. Finally the P50- Average ice case delivered by the database is giving the possibility to design to deliver most of the production without over capacity, making it the best ground for business decision making.

Summary

This chapter described all the process of implementing the simulation, from understanding the process of supply chain affected by ice, through analysis of different supply chain capacities affected by ice scenario, to a final economic evaluation for selected supply chains based on their performance. The process is done in detailed with the input and analysis of the ice data that was given from the Metocean Department at Shell. This information is the base for all simulations run with SALSA. The results are obtained from many simulations made with the tool to try to find a solution to the problem of robustness in the LNG supply chain under Arctic conditions.

The chapter is divided first in the location of the example case used to make the simulations. The Yamal Peninsula is a region being considered for oil and gas exploration by Russia and as it is located in the Arctic, it gave the right conditions to develop this research project. The route selected gave a location on where to focus over ice information would be gathered and perform the supply chain evaluation. It is a disappointment that even under mathematical analysis the ice conditions weren't reproducible in SALSA, therefore the decision to use three main ice scenarios of Heavy...
(P10), Average (P50) and Mild (P90). After this decision was taken, yearly runs were made over different combinations of supply chains using the concepts of the design for an LNG supply chain under Arctic conditions (Conventional, Ship to Ship and Hub to Ship). Capacities were altered over the transportation elements to observe where the weaknesses or strengths were for each design.

To make the results closer to a real business case decision, an economic evaluation was made. This evaluation compared the investment required to implement the capacities of the supply chains and their designs against the revenues obtained from the production it allowed the process to reach. The best performing supply chains in both operational and economical term were assessed against a 30 years historic data. The objective of this research project is to identify a robust supply chain and being able to deliver production in variable ice over the years, disrupting the conventional process was the target to be found.

After analyzing the results the findings are useful to define a good ice scenario to design a supply chain under Arctic conditions. Even though also for the example case used in the research project the choice was made for a conventional supply chain with 22 LNG carriers of 100.000m³ cargo capacity and a storage tank of 280.000m³ capacity, this answer is too punctual for the case and further study will be done.

It was also important to notice how the decision over a specific ice scenario selection will affect the overall performance (operational and financial) of the supply chain design. At least for the example case, P50- Average ice resulted in a scenario that offers an environment from which conclusions can be estimated. Using this scenario the estimated design capacity for the supply chain was in balance to a good production level and therefore positive financial outcome.
6. Future implications

After learning about Arctic and how it can affect the LNG supply chain further experience was gained about issues, which should be considered. These are directed mainly at performing the logistics of the supply chain using shipping as the transportation method. Some of the identified issues are described in this chapter for reference in future projects.

6.1. Climate Change

In the media a lot of information can be found over climate change. Over this information the mentioned fact explains how over the last years Arctic has experienced warming and ice cover decrease. Eventually what the scientific publications are expecting is that in the upcoming years the Arctic Ocean will be ice free during the summer months. This might indicate from the observation made on the information used along this research project that also the ice over the winter will give fewer difficulties for navigation, as it will be less thick to break.

Contemplating the possibility of milder ice, many implications are strongly related to that. For example lower requirements for icebreaking capabilities for the vessels transiting around the Arctic Ocean, faster and easier voyages, less icebreaking support, among others. This will be related to the operational and economical side of a real project. But on the input data for sea ice information could also be affecting the simulation results. The information used along the research project and for the example case is 30 year old historic data. This means that the ice was worse than what it is today and what is expected later.

As the information used is historic information, to perform future simulations the sea ice data should also be accordingly to expected ice seasons to come. This will allow to making the design of the supply chain according to the expectation and realistic situation in the Arctic, as well as the performance results could be closer to reality.

6.2. Icebreaker support

In Arctic shipping is an efficient and effective mode of transport. Due to Arctic environmental conditions vessels intending to navigate there need to be specially equipped. The equipment required can be for example hull reinforcement, propeller increase, powered engine and steering gear strengthening. There are different classifications levels that rule how vessels perform in the Arctic seas according to their features and special characteristics against ice conditions (mainly ice thickness). The ice classification level then is related to the thicker the ice a vessel is intended to navigate in, then more strength and power the vessel requires. Next to the ice classification, also the operational profile can intervene, for example as independent navigation, escorted navigation and according the variation in ice conditions (thickness, ridges, icebergs, concentrations, drifting ice, etc.). Finally, not all ice classified vessels can go through all types of ice and most likely a specialized icebreaker will have to support the navigation operation.

Icebreaking support is one of the operations considered under the term of Ice Management. Currently there is limited experience and research is being done in order to develop knowledge on this issue. As short theory, it is also not predictable when icebreaking support would be need and how it should be best performing for a continued
and large navigation operation. The LNG supply chain is sailing intensive and it would be expected that icebreaking support could be required at some point. Unfortunately no reliable information is available to support how to do this and simulated in a tool like for example SALSA.

Implementing the simulation of the icebreaking support and operation would bring performance results closer to reality for an LNG supply chain under Arctic conditions. Even though there are not so many resources available to develop this behavior in the simulation, from the experience gather during the research project a proposal to implement in SALSA is described in Figure 6.1 as the expected Icebreaker’s operation states are shown.

According to the figure, there could be two possibilities for an Icebreaker to support the voyage of a LNG Ice Carrier:

The first one will take place after the voyage of the LNG Ice Carrier begins. During the voyage an Ice Event takes place and the LNG Ice Carrier’s trip is considerably affected or stopped. The call to support from an Icebreaker is then made and the Icebreaker begins sailing towards the LNG Ice Carrier in distress (#1). The Icebreaker is then considered "loaded" as it is supporting the LNG Ice Carrier until the end of the Ice Event (#2). After this, the Icebreaker is released ("unload") and will wait for next event according to waiting times set in the SALSA. In case there are no new vessels to give support to, the Icebreaker would return "empty" to the production port. In other case, if a call from another LNG Ice Carrier being affected by a new Ice Event, the cycle would begin again.

The second alternative is to start the support from the production port. If the Ice Event has already started, then the LNG Ice Carrier could make the support call and the Icebreaker would accompany the vessel until the Ice Event is finished. In this case also states of Empty, Load and Unload exist for the Icebreaker, except the trips in between are continuous in either a loaded or empty. Once again waiting times should be set to make the operation behavior clear for the Icebreaker.
Some functional requirements for SALSA have been described as a base to begin the study of an implementation of this simulation process:

1. **Objective:**
   - To simulate icebreaking support for the LNG supply chain under Arctic conditions.
   - Icebreaking support is required during specific ice events in a simulation where the LNG carriers are not able to continue the navigation journey due to heavy sea ice, ridges, drifting ice, etc.

2. **Functionality:**
   - Simulate icebreaking support to LNG ice carriers.
   - Determine a fleet size and navigation characteristics for the icebreakers as for example maximum speed and impact over it when sailing independent or in convoy.
   - Icebreaker will support at least one vessel at a time with a maximum capacity to be set out by the navigation characteristics.
   - Icebreakers will be called upon for the ice leg of the route or where an ice event is affecting the travel behavior over a leg. It shouldn't necessarily be at the beginning of the leg, but it should be possible to request assistance after the voyage has begun.
   - Not in all ice events and icebreaker would be required. Specifics events should be created to be used for icebreaking support.
   - The icebreaker will be affected by the ice event over the leg as well, but due to its characteristics it should be expected to reach the LNG ice carrier in distress.

3. **Input**
   - The user should define the occurrence of the Ice events along the voyage over the ice leg.
   - Icebreaker fleet size and operational characteristics (speeds, fuel consumptions, maximum number of convoy vessels, waiting times, etc.)

4. **Output and performance**
   - Utilization for operation, free voyage or supporting voyage.
   - Voyage and port (queue) times.

During the development of this research study a project initiated with the analysis of Icebreaking support and optimization under Arctic conditions. The results of the first stage of this additional project have been delivered to Shell. There are still many points to be considered in the simulation for icebreaking support. More or new techniques can be developed with new hull designs or power options for the vessels sailing in Arctic, so more contact with sailing experts should be done. Stasco (Shell Shipping and Trading Company) could provide good support in gaining further knowledge in the operation of Icebreakers and therefore enrich the simulation process within SALSA.

### 6.3. Expansion of the example case

The example case used during the analysis of this research project is very specific. For the first steps to gain knowledge has proven to be an enriching process, but more insights
are still to be explored. Some expansion issues can be related to the market locations, variation in the transshipments points (for either case of the Ship to Ship or the Hub to Ship supply chain designs), capacities on the LNG carrier fleets (for ice carrier or the open water ones), route alternatives and of course icebreaking assistance. Also the implementation of future ice scenarios instead of historic ones as was explained before as well as other type of environmental events that are affecting logistics in the Arctic area. These weren’t all considered in this research project due to limitation in information, resources and time. For the objective of understanding the impact of sea ice over the supply chain for LNG to identify a robust supply chain was found for the example used, but it should be possible to bring the simulations closer to reality. The example case used for the research should be only the beginning to trigger new horizons in findings about LNG logistics under Arctic conditions.

6.4. Creation of quick assessment tool for LNG logistics under Arctic conditions

One of the most desirable results from a research project like this one would be to be able to define an easy method on how to assess a supply chain concept for an Arctic situation like the one described along this report. An endorsement on how such a method could deliver a quick tool for this purpose can be seen in Figure 6.2. The figure is first divided into quadrants related to the expected risk of having a stable delivery of LNG or an unstable one, depending on the disruption of sea ice level. This means that axis X begins with Open Water (or no ice) to the farthest right into Heavy Ice. Quadrant #1 establishes a stable delivery, as there is low risk since the ice level goes from non-existent to mild, therefor no big disturbances would be expected. Quadrant #2 is found to be non-likely in the extreme case of heaviest ice level once the concepts operation is not able to withstand the disruption of the sea ice, so the idea to have a stable LNG delivery is difficult to conceive. On the contrary, quadrant #3 is not likely because low disruptions due to an open water or mild ice allow a stable delivery and not an unstable one as stated by this quadrant. Finally quadrant #4 denotes a high risk in the delivery of LNG as with heavy ice levels an unstable situation could occur and therefore a non-robust supply chain for LNG. The quadrants in the middle are not really qualified as more knowledge should be gained, but of course a stable delivery regardless of the ice is the objective to achieve for the LNG supply chain.

Each supply chain concept should be placed around the matrix depending on their performance in operational terms according to the ice levels. For example the conventional supply chain concept will oscillate in performance along the different ice levels according to the capacity of its elements and strategy to be robust regardless of the ice. Some combinations of course won’t be able to deliver good performance and therefore will be located in the lower side of the matrix in the unstable delivery. The Hub to Ship supply chain concept deliver the most stable results as it is the one which has the most elements to be able to use strategies of robustness, this is said as the ice fleet and the open water fleet is focused on its correct environment, no slavery between fleets and only consideration for loading berths and distances should be better assessed. But these ideas are taken from the experience gained over the restricted amount of results obtained during this research project and further knowledge is needed to complete and improve this tool.
The idea with such a matrix is to continue analyzing alternatives and be able to completely classify each supply chain concept along the right quadrants. As mentioned on the recommendation of expanding the example case, there could be other variables playing an important role in the results of a supply chain under Arctic conditions like investment cost, supply chain capacity, distance, among others. Implementing these criteria would most definitely change the shape and area covered by each supply chain concept on its robustness and depending on the different ice levels. Consequently this should not be considered as the final results of the research project, but merely an idea to be continued. Once more insights are gained over how the supply chain behaves, the right variable could be implemented in the matrix and therefore the right shape and locations of the supply chains to have a quick assessment of the supply chains under Arctic conditions can be finally made true.

Summary
This section described the future subjects that can be improved and further studied to obtain more detailed results for the LNG supply chain under Arctic conditions. There are always more issues that can be improved and it is a relief to be able to define them. Once the first stage of this research project is finished, being able to point out where more knowledge can be found to gain more value is important and in this case is not different. Improving in the information for sea ice and other Arctic environmental characteristics will help to assess the future of a project in this area. Being able to implement other weather events and in accordance to what is expected due to current climate changes will situate a project for more realistic performance results from the simulations.
Then being able to implement simulation tools for SALSA with operations dedicated to
Arctic conditions will deliver more results to evaluate the performance of the supply chain.
In this case icebreaking support for navigation around the sea ice covered area has been
one of the identified items. With more research and experience this will improve a key
point when considering operations in Arctic.
Finally SALSA as a tool for this research project can release more insights about the
supply chain; once more details are implemented in the model. So the expansion of the
example case means more effort but closer to reality results.
7. Conclusions and recommendations

During this research project supply chain concepts for LNG production in an Arctic area were designed to assess robustness. First getting familiar with the Arctic, its characteristics, weather conditions, risks and stakeholders was the first step to understand the unconventional environment it is for logistic operations. Second comprehension of the LNG supply chain and its process gave way to create supply chain alternatives to deliver the product from an Arctic location to the demand markets. A selection of these supply chain concepts was done after collecting information and experiences of experts from Shell. Using a simulation tool owned by Shell (SALSA) the supply chain concepts of Conventional, Hub to Ship and Ship to Ship were modeled. An extensive amount of simulations was carried out for these models. Key performance indicators were giving the answer over which supply chain concept could overcome the disruption of sea ice scenarios (heavy, average and mild ice scenarios). An economic evaluation was done over the best performing concepts to balance operation against financial results. Finally the models were put to the test with a 30 year historic sea ice scenario to find out which one was delivering a robust response against the impact of ice versus its design.

The conclusions for this research project will be described following the same structure of the report. After the conclusions a set of recommendations for future projects can be found.

7.1. Conclusions

The conclusions of the research project done on the LNG logistics under Arctic conditions are presented below.

Arctic

- Arctic is not only a remote area from the demand markets, additionally its harsh weather conditions makes it a challengeable area to work on logistics.
- The unique characteristics on the weather conditions for each of the seas surround the Arctic Ocean add further difficulty. This difficulty lies in the individualization of each project according to the area it will be located. Some general conditions should be considered in the preparations for logistic operations, but detailed information on weather and geographical conditions will be required.
- The details of the information will allow creating a plan and clear schedule for logistics operations around the Arctic seasons and the specific location. This is the first step to define a controlled strategy to perform logistic activities in the Arctic.
- Besides the conditions related to Arctic’s geographical location, it has also become a sensible area due to climate change. For this reason the stakeholder approach is an important subject to cover when a project for oil and gas exploration is thought for development. The stakeholder research in this report could provide a good first contact to be introduced into a more in-depth approach for local stakeholders and governments.
- Each country might have its own legislation for exploration, production and transportation within its borders. For maritime purposes, there are requirements to allow vessels to navigate in Arctic waters. These requirements are stated as Ice
Classification and it will determine the characteristics of the vessels and their way of operation (independent or assisted). Assisted navigation is one of the activities related to ice management, which is a subject currently being studied by companies who want to develop various projects in the Arctic.

LNG Supply Chain

- Natural gas is a fossil fuel that can be transported in diverse ways. Currently LNG is the most growing method to transport big quantities of natural gas due to the flexibility it gives in reaching distant and dynamic demand markets. Since Arctic is located far away from the markets, the cost of natural gas transport development gives LNG the preference as transport method. Moreover due to the increasing demand of LNG more research and technology is being developed. This could further help to improve feasibility of the different supply chain concepts presented in this project.

- Arctic conditions can affect the operation of logistics, therefore good planning and scheduling is critical to perform at minimum disruption. However to be able to overcome the disruptions caused by Arctie conditions, resilient strategies in combination with sufficient capacity among the supply chain elements will make the delivery of LNG regardless of the Arctic conditions a success.

- There are many performance indicators that can give a first impression of how the supply chain is behaving according to its elements and external factor affecting its operations. To be able to complete the overview of the supply chain outcome, the combination of the indicators will always further complement and give direction into which could be areas for improvement. For example the LNG supply chain, production level and deliveries are the first indicators to assess. After this point, digging into the production process, tanks, berths & ports, route, shipping and delivery port performance indicators, the supply chain can better understood on where to improve or to further develop strategies to work around possible disruptions.

Ice data

- The methodology to implement ice information into SALSA for simulations was created. This methodology is now supported after obtaining the results for this research project and could be used in future projects. The input is the ice data information given by Metocean and the outcome will be the impact of sea ice to affect voyage duration for the simulations.

- The utilization of ice scenarios (P10- Heavy Ice, P50- Average Ice, and P90- Mild Ice) already determines a certain risk for the supply chain design. These scenarios were proven in first instance to be an acceptable design base against the comparison of the percentiles obtained from the historic data. In this case, the P scenarios given by the database contained the percentiles, so they would be an acceptable level of ice impact to analyze a supply chain system. In second instance, when the supply chain cases were run against the full 30 years ice historic data, the results showed to be in accordance to what the P scenarios were representing. A third practical reason to have selected the P ice scenario was due to speed in performing the simulations and obtaining numerous results. However running the simulation for three different ice scenarios can be time consuming. From the results of this research project using a P50- Average Ice
scenario was recognized to be sufficient for the assessment of the supply chain design.

• Preliminary fleet calculations give an easy and quick method to determine required fleet size, related to ice scenarios and ship characteristics. The main advantage is that the creation of such a calculation sheet doesn't need to be included in SALSA to have a wider access for people interested in developing a project case, but eventually when required the tool will be available.

• The format in which the ice information was given couldn't be implemented in SALSA and an alternative to use this information was created. Based on the impact over the voyage duration the seasonality of the ice was not reproducible with a probability distribution to create stochastic events, therefore deterministic cases were defined to run the simulations.

SALSA simulations

• The results of the simulations are delivering results that were in line with the expectations and preliminary calculations. This indicates that the simulations are behaving as assumed and supports further what was believed for Arctic supply chains.

• The advantage of the simulations is that it gives details on performance indicator outcomes for example shortage of storage capacity.

• LNG Seasonal Production can be used in the advantage of shipping, as the voyage time is high when reduced production begins. Detailed scheduling should be done to coordinate this.

Economic Evaluation

• There are many robust supply chain alternatives. The balance between operation and project finances will help in the assessment.

• Economic balance will be giving the final selection for the best performing supply chain operations. At the end real cases are meant not only to work on perfect performance, but also how much investment and return is going to be recovered from the operations.

Robustness

• The availability of information plays an important role in the design of the supply chain. The desired circumstance is to have all required information available, but this is not always the case. For this reason there are different ways to adapt or gain knowledge. In some cases, the design will just have to comply with whatever information is available and be able to collect more information along the way. In other cases, the design must be done taking advantage of the information that is already available. And in many cases, an expensive supply chain design is implemented in order to compensate for the lack of information.

• At least for the example case studied during this research project an answer to which supply chain concept could withstand best the impact of sea ice was the Arctic Conventional supply chain concept. The case using 22 vessels of 100,000m³ cargo capacity and the storage tank of 280,000m³ delivered almost 100% of the production and therefore the finances obtained from such a supply chain will obtain the point of equilibrium for a prospect project.
7.2. Recommendations

Not only conclusions have been drawn but some recommendations can be described for future projects to be evaluated:

- **SALSA** is a good simulation tool, but further development for Arctic conditions is required to obtain better results. For example:
  - Hub and Ship to Ship cases are still in development and limitations sometimes were affecting the simulations.
  - Icebreaker analysis and optimization was delivered for first stage. More research on operation for ice management and icebreaking assistance should be done, to translate into a simulation behavior for SALSA.
  - Climate change is affecting the extension of sea ice. This will impact the simulation results as open water time window increases. For future studies, this trend should be considered and improved data sets could be used in SALSA.

- Performance and financial indicators give a sensible criterion to select between the possible designs. Once a narrowed choice is done, further indicators on environmental, technical challenge or social areas can help take this selection to a deeper level.

- The expansion of the example case used during this project will bring closer to reality results. Details on process, vessel characteristics, port activities, etc. will deliver a more complete overview of how the supply chains behave.

- Better assessment of the ice and the real impact over shipping performance. The assumption used here is that the Ice Carriers even thought are moving slower, they will always be able to cross heavy ice. In reality there is experience that this is not always the case and there will be opportunities where the vessels will get stuck in the ice. A more in-depth study of this support should be carried out in order to understand and be prepared to such events.

- On ice management and icebreaking assistance, sharing of information is very important. By allowing all interested parties in knowing arrival times or possible delays, gives the opportunity to prepare for shipping reaction as well as LNG production planning. Currently using advanced communication equipment, and location devices as GPS or radio signaling could improve planning and prediction of ice conditions. These tools can help for route selection, possible ice breaking assistance and trip planning.
8. References


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9. Appendix
Appendix 1: Example of seasonal calendar to consider for logistics operation under Arctic conditions

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<td>Ice Thickness (Land Fast Ice Zone)</td>
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<td>Ice Thickness (Polar Pack)</td>
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<td>0.8 to 2.0 m</td>
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<td>Average Temperature (°C)</td>
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<td>Max Temperature (°C)</td>
<td>+4</td>
<td>+3</td>
<td>+2</td>
<td>+6</td>
<td>+11</td>
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<td>Wind (knots) - Average Speed</td>
<td>13.5</td>
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<tr>
<td>Offshore Wildlife</td>
<td>Spring Migration Start: Apr. 1</td>
<td>Spring Hunt Start: May 15</td>
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<td>Fall Migration Start: Sep. 4</td>
<td>Fall Hunt End: Sep. 21</td>
<td>Fall Migration End: Nov. 11</td>
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<tr>
<td>Onshore Wildlife</td>
<td>Polar Bear Cubs are born</td>
<td>Polar Bears Mating</td>
<td>Female Polar Bears Fertilized</td>
<td>Females dig maternity dens and enter dormant state</td>
<td>Polar Bear Cubs are born</td>
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LNG logistics under Arctic conditions

C. Higuera
## Appendix 2: List of Contributors

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<tr>
<th>Company</th>
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<th>Name</th>
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<td>DNV</td>
<td>Arctic Technology</td>
<td>G. Cammaert</td>
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<tr>
<td>University of Stavanger</td>
<td>Arctic Technology and structures</td>
<td>O. Gudimestad</td>
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</table>
Delft, August 31st 2011

Delft University of Technology
Faculty Civil Engineering and Geosciences
Master Transport, Infrastructure and Logistics

**Subject:** Request embargo for thesis document "LNG Logistics under Arctic conditions"

To whom it may concern,

Through this letter, I would like to kindly request to keep my master thesis document under embargo for the maximum period of time possible or at least a minimum of two years from the date of delivery. This is following the request of the company where I have completed this project.

Thank you,

Catalina Higuera